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## 14. Abstract

**Project #1**

**Background:** Muscle injuries, especially pulls and strains, are among the most common and most frequently disabling injuries sustained by athletes and soldiers. Although injured muscles heal naturally, the regeneration is very slow and often yields incomplete functional recovery. In injured muscle, regeneration begins shortly after injury, but the healing process is rather inefficient and is hindered by fibrosis—that is, scar tissue formation. More importantly, the scar tissue that often replaces damaged myofibers may contribute to the tendency of strains to recur. We have observed that TGF- $\beta$ 1 plays a central role in skeletal muscle fibrosis and, more importantly, that the use of antifibrosis agents that inactivate this molecule, such as suramin (a Food and Drug Association [FDA]-approved drug that prevents fibrosis due to skin disorders), can reduce muscle fibrosis and consequently improve muscle healing, resulting in nearly complete recovery after laceration or strain injuries.

**Objective/Hypothesis/Specific Aims/Study Design:** We plan to develop biological approaches based on suramin to efficiently prevent the scarring process by blocking the action of TGF- $\beta$ 1; we will determine the appropriate time at which to administer suramin and the optimal suramin dosage after muscle contusion, a common military injury (**Technical Objective #1**). Because we have observed that suramin can both enhance muscle regeneration and neutralize the fibrotic effect of TGF- $\beta$ 1, we also propose experiments designed to further evaluate the beneficial effects of suramin on muscle regeneration (**Technical Objective #2A**). Finally, we will determine if this effect is mediated through suramin's interaction with muscle growth regulators, particularly its possible down-regulation of myostatin or up-regulation of follistatin (**Technical Objective #2B**).

**Supplemental proposal 1 Objectives:**

**Supplemental Objective 1:** To determine the pharmacokinetics of suramin delivery when administered via intramuscular injection in mice for the treatment of skeletal muscle injuries.

**Supplemental Objective 2:** To evaluate the beneficial effect of decorin, another antifibrosis agent, on muscle regeneration and healing and its mechanism of action.

**Supplemental proposal 2 Objectives:**

**Supplemental Objective 1:** To evaluate whether decorin's beneficial effect on muscle healing is mediated through its influence on muscle inflammation. **Hypothesis:** Decorin improves muscle healing by influencing muscle inflammation.

**Supplemental Objective 2:** To investigate whether decorin's beneficial effect on muscle healing is mediated through MSTN or FLST, two important regulators of muscle growth. **Hypothesis:** Decorin promotes muscle healing by down-regulating MSTN or up-regulating FLST.

**Supplemental Objective 3:** To evaluate whether angiotensin II receptor blockade after injury represents a potential non-invasive approach to improve muscle regeneration and repair after military-related muscle injury. **Hypothesis:** Angiotensin II receptor blockade will improve muscle healing after injury.

**Relevance:** These studies should further our understanding of the muscle healing process, facilitate the identification of new techniques to promote efficient muscle healing, and contribute to the development of innovative therapies for various types of muscle injuries and diseases, such as muscular dystrophies.

**Project #2**

**Background:** Muscle injuries are very common musculoskeletal problems in traumatology that arise frequently in military training and combat. Injured skeletal muscle undergoes a natural process of regeneration; however, fibrosis—the formation of fibrous scar tissue—hinders this process and precludes the complete recovery of

muscle function. Prevention of fibrosis could improve injured skeletal muscle healing; however, it often is not possible to treat muscle injuries before fibrosis occurs.

**Objective/Hypothesis:** We hypothesize that matrix metalloproteinase type 1 (MMP1), a collagen-digesting enzyme, can improve the microenvironment for muscle regeneration and accelerate healing by digesting existing scar tissue within recovering muscle. Further we hypothesize that MMP-2 can enhance muscle cells migration and regeneration, reorganize muscle structure and accelerate muscle healing after injury.

**Specific Aims/Study Design:** First, we will culture muscle-derived fibroblasts and myogenic cells *in vitro* in the presence of MMP1 and assess its effects on fibroblast proliferation and collagen deposition (**Technical Objective #1A**) and myogenic cell migration and differentiation (**Technical Objective #1B**). We then will inject MMP1 directly into normal (noninjured) skeletal muscle to determine the safest and most effective dose of MMP1 *in vivo* (**Technical Objective #2A**). Next, we will evaluate the ability of MMP1 to digest fibrous scar tissue present within injured skeletal muscle and, by so doing, to enhance the regeneration and functional recovery of injured skeletal muscle (**Technical Objective #2B**). Finally, we will attempt to extend the effective half-life of MMP1 in fibrous scar tissue by genetically engineering myoblasts and muscle-derived stem cells (MDSCs) to express MMP1 (**Technical Objective #3**).

**Supplemental Proposal 1 Objectives:**

We will evaluate the effects of MMP-2 on myogenic cell migration and differentiation *in vitro* (**Technical Objective #1**). We then will use MMP-2 enhance muscle cells migration and regeneration to improve the functional recovery of injured skeletal muscle *in vivo* (**Technical Objective #2**). Further, we will attempt to assess the relationship between MMP-1 and MMP-2 during muscle healing (**Technical Objective #3**).

**Relevance:** The study results generated by the proposed project should shed further light on the effects of scar tissue on muscle healing after injury and could facilitate the development of methods by which to eliminate scar tissue and enhance the regeneration of muscle damaged by military- or sports-related injuries or diseases.

### **Project #3**

Our preliminary studies point to a close developmental relationship between vascular endothelial cells and myogenic cells in the adult human muscle. We have, indeed, characterized two novel populations of muscle-derived, non-satellite cells that exhibit dramatic myogenic potential in culture and *in vivo*: genuine vascular endothelial cells and cells co-expressing markers of both myogenic and endothelial cell lineages, which we have named myo-endothelial progenitors. Both cell populations can be purified by flow cytometry as endothelial (CD56- CD 34+ CD144+) and myo-endothelial (CD56+ CD34+ CD144+), and cultured for several weeks without losing their myogenic potential. In our preliminary experiments, the myogenic potential *in vivo* of myo-endothelial progenitors is dramatically higher than that of endothelial cells, which are themselves much more efficient than regular myogenic cells. We propose experiments to further assess the respective myogenic potentials of human muscle-derived endothelial and myo-endothelial cells, which will be compared qualitatively and quantitatively following injection into the injured SCID mouse muscle. Besides myogenesis, the development of other cell types, notably endothelial cells and pericytes, upon intramuscular injection will be examined. We hypothesize that upon myo-endothelial cell transplantation, high rates of donor cell survival and/or proliferation will promote skeletal muscle regeneration by generating more donor cells that can subsequently participate in the regeneration process. We propose a set of experiments to determine the rate at which these different populations of human muscle-derived cells survive and proliferate at different time points after injection, and to evaluate if such differences might affect the regeneration capacity of the cells after transplantation into the skeletal muscle. We will also perform experiments to investigate if these various human muscle-derived cell populations implanted in mice *via* intramuscular injection undergo self-renewal. We will also use a previously described protocol to determine if the donor-derived muscle precursor cells isolated from the skeletal muscle of primary recipient mice can be re-transplanted into the skeletal muscle of secondary recipients and improve skeletal muscle regeneration. To this aim, we will retrovirally modify human-derived



myogenic, endothelial and myo-endothelial cells to express GFP. This will enable us to rapidly count the GFP-expressing cells isolated from primary recipients and sort them with high purity for re-transplantation into secondary recipients. Finally, we will also check if cell fusion between donor cells or between donor and host cells plays a significant role in muscle regeneration by these different subsets of human cells.

**Supplemental Proposal 1 Objectives:**

- 1- Characterize the potential of pericytes to give rise to a full array of differentiated cells following transplantation into the injured skeletal muscle. We will determine, in a xenochimeric model, whether pericytes can, besides myofibers, regenerate other cell compartments that are fundamental to wound healing and tissue regeneration: blood vessels, connective tissues, nerves.
- 2- Determine the potential of pericytes to give rise to more primitive stem cells (auto-renewal), and/or to committed muscle progenitor cells (satellite cells) on transplantation into the injured skeletal muscle. Long-term and iterative transplantation experiments will be performed in order to understand whether pericytes can not only regenerate skeletal muscle, but do it permanently. This is a key point to be taken in consideration in the perspective of transplanting these cells into patients.
- 3- Master the long-term culture of pericytes while maintaining their developmental potential intact. The biology of pericytes *in vitro* will be scrutinized in order to validate culture protocols allowing to obtain large lots of transplantable cells.

**Project #4**

**Background:** As progress toward understanding the basic biology of stem cells continues to grow, it is of vital importance that researchers maintain a focus on therapeutic applications of this technology by investigating preclinical models. Members of our laboratory have identified a mouse muscle-derived stem cell (MDSC) population that exhibits a highly enhanced ability to regenerate skeletal muscle in a muscular dystrophy model. Transplantation of this cell population results in significantly more efficient regeneration of skeletal muscle fibers and a significantly larger area of regeneration than does myoblast transplantation, a therapy that has already been tested in human clinical trials in both the United States and Canada. The isolation and transplantation of the human equivalent of these mouse MDSCs likely would improve the outcome of cell therapy for muscular disease and injury, including injuries frequently sustained by military personnel.

**Objective/Hypothesis:** The objectives of this project are 1) to identify the human stem cell populations that promote the most efficient skeletal muscle regeneration in a preclinical mouse model of muscle regeneration and Duchenne muscular dystrophy (DMD) and 2) to identify the optimal conditions under which to expand cell populations and obtain therapeutically relevant doses.

**Study Design:** We will screen human muscle-derived cells for a molecular and behavioral profile that correlates with efficient skeletal muscle regeneration in a preclinical model of DMD (Technical Objective #1). We also will identify the cell culturing conditions that best facilitate expansion of the potent populations (to therapeutically useful quantities) while maintaining the cells' phenotype and regeneration efficiency (Technical Objective #2).

**Supplemental Proposal 1 Objectives:** While ongoing projects are focused on characterizing how to identify and maintain the stem cell phenotype of human MDSC, we are also initiating studies to identify optimal conditions for the cryostorage of these cells. We will build on the Live cell imaging (LCI) technology as a tool identify the optimal conditions for the processing of the cells as a biologic product for therapeutic applications. LCI provides live viewing of the behavior of a stem cell population in culture and allows us to obtain numerous real-time measurements at the single cell level. The result is a detailed behavioral phenotype of the stem cell population which can be linked to in vivo outcome measures. We will use this tool to follow the changes of cell phenotype in response to temperature changes and fluctuations.

**Relevance:** This project represents a critical step in cell therapy: Screening potential cell candidates and studying expansion kinetics and limits to generate stem cells for use in cell and gene therapy. This project is unique in that it takes the next step in moving muscle stem cells toward clinical application by investigating how to develop a safe and standardized approach by which to expand stem cell populations. The stem cell screening and expansion techniques that we plan to develop will facilitate the use of cell and gene therapy for myriad musculoskeletal injuries and diseases.

### **Project # 5**

Congenital muscular dystrophy (CMD) is a group of severe forms of muscular dystrophy leading to early death in human patients. The majority of cases are caused by genetic mutations in the major laminin that contains the  $\alpha 2$  chain (formerly named merosin) in the muscle basement membrane. The early morbidity/fatality and the lack of effective treatment require urgent search for novel therapeutics. Previously, we utilized mini-agrin, which has been proven to have a therapeutic effect in transgenic MCMD mice, to treat MCMD mice by AAV vector. Our preliminary studies showed that over-expression of mini-agrin protein by AAV vector greatly improved general health and muscle morphology in MCMD mice. However, the treated disease mice still developed gradual paralysis and displayed shorter life span than wild type mice. To further improve the current gene therapy paradigm, with the advanced AAV technology and muscle biology knowledge, we will vigorously test our hypothesis: whether muscle pathogenesis can be improved by inhibition apoptosis or promoting muscle growth. The specific aims are the following:

**Aim1:** To investigate whether muscle pathogenesis can be improved by delivery of BCL2, an anti-apoptotic gene, by AAV vector in MCMD mice. Mice that lack laminin  $\alpha 2$  show severe muscle loss, poor regeneration, and a greatly shortened lifespan. A role for apoptosis in pathology of laminin  $\alpha 2$ -deficiency has been suggested by histological and *in vitro* studies, as well as transgenic studies. In this study, we will explore the potential therapeutic effect by delivering AAV-BCL2 vector into MCMD mice.

**Aim2:** To examine whether therapeutic effect can be obtained by delivery of insulin like growth factor 1 (IGF-1) gene, which can promote muscle growth, by AAV vector in MCMD mice. The MCMD mice show muscle atrophy and enhanced fibrosis as seen in human patients. Genes that promote muscle growth and inhibit fibrosis is theoretically beneficial for congenital muscular dystrophic muscle. Myostatin blockade, one of the strategies to promote muscle growth, has been shown to have a severe side effect of increasing postnatal lethality in MCMD transgenic studies. The reason for the side effect is due to significantly less brown and white fat in the absence of myostatin. In our preliminary studies, we observed that myostatin blockade significantly increased muscle weight, as well as decreased fat tissue in normal mice. However, over-expression of IGF-1 in normal mice only increased muscle weight without losing fat. Considering less fat will result a severe side effect, we will deliver IGF1 gene to MCMD mice by AAV vector to study whether a therapeutic effect can be achieved in this proposal.

Upon completion, this project will establish complementary therapeutic strategies to combat the severe congenital muscular dystrophy in animal model, setting the base for the development of a clinically efficacious gene therapy strategy.

### **Project # 6**

**Background:** Elegant studies show that certain cytokines trigger the activation of nuclear factor kappaB (NF- $\kappa$ B) mediated by phosphorylation and degradation of the NF- $\kappa$ B inhibitory protein, IkappaB $\alpha$ . Downstream effects of pathological NF- $\kappa$ B activation in skeletal muscle include the inhibition of new muscle formation and the degeneration of existing muscle. *In vitro* studies support the potential that the IkappaB $\alpha$  superrepressor (IKBSR), an IkappaB $\alpha$  genetically engineered to prevent its phosphorylation, can prevent the activation of NF- $\kappa$ B in skeletal muscle and could ameliorate or prevent muscle wasting. Our preliminary studies demonstrate the novel determination of inhibition of activation of NF- $\kappa$ B by cFLIP.

**Objective/Hypothesis:** The proposal will explore the mechanism of muscle wasting in an *in vitro* model and develop novel gene transfer vehicles testing the hypothesis that gene transfer strategies can promote muscle regeneration toward a goal of improving muscle bulk and strength in the setting of injuries or diseases that cause muscle atrophy.

**Specific Aims:**

Aim 1: To characterize an *in vitro* model of cancer-induced muscle wasting in primary muscle cells and in stable muscle cell lines expressing IKBSR or cFLIP.

Aim 2: To clone, rescue, and purify AAV serotype 1 vectors carrying IKBSR or cFLIP and characterize expression and function *in vitro* in anticipation of future use in an *in vivo* model of muscle wasting.

**Study Design:** We will characterize an *in vitro* model of muscle wasting studying NF- $\kappa$ B activation, the ubiquitin-proteasome system and caspase activation. We will test whether genetic modifications to muscle cells will confer a benefit by blocking pathways of muscle degeneration. We will develop gene transfer vectors designed to promote muscle regeneration.

### **Supplemental Proposal 1 Objectives:**

**Supplemental Objective 1:** To test gene transfer approaches in an *in vivo* model of cachexia

- A. Test AAV carrying IKBSR for treatment of cancer cachexia
- B. Test AAV carrying cFLIP for treatment of cancer cachexia

**Supplemental Objective 2:** To test peptide transduction approaches of inhibiting NF- $\kappa$ B activation as treatment for muscle cachexia

- A. Test peptide transduction in an *in vitro* assay of muscle cachexia
- B. Test peptide transduction in an *in vivo* assay of muscle cachexia

**Relevance:** The ability to promote muscle regeneration in the setting of focal or generalized muscle loss could confer significant clinical benefit in the setting of focal neuropathic or other processes that cause muscle atrophy or chronic illnesses that cause cachexia.

### **Vector Core:**

#### **Background:**

The newly established molecular biology laboratory (MBL) will be a Vector Core for the project “Molecular Therapy of Muscle Repair”. The goal of this core is to construct vectors such as adeno-associated-, adenoviral- and retroviral vectors for this project. Besides the tissue specific promoter and optimal serotype of vectors in the project #5 and project #6, we will develop a newly modified AAV vector, called the Tet/on and Tet/off AAV vector. This new vector is very useful to ameliorate the acute inflammatory during the early time of muscle injuries. The gene in Tet/on vector will be induced to express the therapeutic gene in the presence of doxycycline, an antibiotic. To avoid the toxicity caused by gene over expression, the vector will be turned off at the time when the muscle is healed.

#### **Objectives:**

Objective 1: To continue the production of AAV vectors for the following genes

- A: Decorin for project #1
- C: Mini-dystrophin gene
- D: MPRO (myostatin propeptide) for project # 5

Objective 2: To construct the following genes into AAV vector

- A: MMP1 for project #2
- B: IKBSR for project #6
- C: cFLIP for project #6

Objective 3: To design the new AAV vector containing muscle tissue specific promoter.

Objective 4: To develop the adenoviral and retroviral vectors.

### **BioReactor Core**

The Bioreactor Core serves as a resource for project investigators in need of dynamic cell population analyses. This core uses the Automated Cell CytoWorks™ (ACCW) robotic system to characterize and compare various populations of adult-derived stem cells. The system, in theory, can give the investigator a read out of 20 to 30 different parameters in the form of a “Phenoprint©”. We have also planned to set up internet technology to share the information generated in the core facility and thus facilitate further study and development of adult-derived stem cell-based therapies by members of the broader scientific community.

**MicroCT Core**

Dr. A. Usas operates vivaCT 40 (Scanco Medical) imaging system that enables nondestructive 2-D and 3-D visualization and quantitative analysis of mineralized matrix volume, density and other structural parameters of bone tissue. We are able to perform live animal imaging while they (mice or rats) are put asleep under inhalation anesthesia. VivaCT 40 system allows us to perform multiple scans on the same animal at different time points; therefore we are able to reduce the number of animals required to complete the experiment and cut the cost for animal housing. We can also perform imaging on organs and tissue specimens (calvaria, spine, extremities, muscles, etc.) harvested after animal euthanasia and stored in fixative solution for extended period of time.

We continue to investigate skeletal muscle vasculature using contrast-enhanced micro-CT imaging. One method that has been successfully applied involves transcardiac perfusion and injection of Microfil<sup>®</sup> silicone rubber compound. After Microfil polymerization that takes 4-6 hours in room temperature blood vessel network in post-mortem tissues of non-surviving animals becomes radiopaque and easily detectable by micro-CT. Another contrast agent for vascular imaging is Fenestra VC, which can be administered repeatedly to animals via single dose administration into tail vein. With Fenestra VC, the delayed uptake by liver cells produces an agent with superior blood pool imaging properties that last for several hours after injection. We are planning pilot experiments to investigate whether Fenestra VC can be used to visualize peripheral vasculature in living mice.

**Administrative Core**

The Administrative Core of the Stem Cell Research Center (SCRC) is directly responsible for ensuring the proper function and integration of the Research Laboratories (comprising the Core Research Laboratories, Affiliated Laboratories, and Research Core Facilities), the Clinical Trials Unit, and the Educational Programs that constitute the SCRC. The Administrative Core provides administrative services to all SCRC personnel, supports the ongoing activities of the SCRC, and provides a mechanism for regular evaluation of the SCRC. The Administrative Core also is responsible for fulfilling the secretarial, budgetary, and grant application and manuscript preparation needs of SCRC personnel. In addition, this Core also facilitates collaboration between SCRC researchers and scientists working in designated Collaborative Institutes or other, non-affiliated laboratories.

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Project #1: Muscle Injuries, suramin, Fibrosis, TGF-beta1, myostatin, follistatin, decorin, Losartan			
Project #2: Muscular dystrophy, AKT1/Foxo/atrogen1 pathway, glucocorticoids			
Project #3: Muscle, stem cell, vascular endothelium, tissue regeneration, cell therapy Project #4: muscle regeneration, human myogenic stem cells, expansion, cell aging, population doubling, fibrosis			
Project #5: Adeno-associated viral vector (AAV), BCL-2, IGF-1, Laminin, myostatin, congenital muscular dystrophy			
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**Project # 1**  
**The use of suramin to improve muscle healing after military-related muscle injuries**  
**(Johnny Huard)**

**Introduction**

Muscle injuries, especially pulls and strains, are among the most common and most frequently disabling injuries sustained by athletes and soldiers. Although injured muscles heal naturally, the regeneration is very slow and often yields incomplete functional recovery. In injured muscle, regeneration begins shortly after injury, but the healing process is rather inefficient and is hindered by fibrosis—that is, scar tissue formation. More importantly, the scar tissue that often replaces damaged myofibers may contribute to the tendency of strains to recur. We have observed that TGF- $\beta$ 1 plays a central role in skeletal muscle fibrosis and, more importantly, that the use of antifibrosis agents that inactivate this molecule, such as suramin (a Food and Drug Association [FDA]-approved drug that prevents fibrosis due to skin disorders), can reduce muscle fibrosis and consequently improve muscle healing, resulting in nearly complete recovery after laceration or strain injuries.

**Body**

**A) Rationale**

**1) Original Proposal**

Muscle injuries are very common musculoskeletal problems, and the experiments described in this application are highly relevant to currently unmet medical needs. Although we do not yet understand all the events required for efficient muscle healing, enough information exists for us to vigorously test the proposed research aims. Our extensive preliminary results, presented below, strongly suggest that researchers working to develop biological approaches to improve muscle healing after injury should focus on the elimination of fibrosis within injured muscle tissue. We have observed that TGF- $\beta$ 1 plays a central role in skeletal muscle fibrosis; the use of antifibrosis agents that inactivate this molecule can reduce muscle fibrosis and consequently improve muscle healing after injury. Although the effect of TGF- $\beta$ 1 can be blocked in various ways—including treatment with a neutralizing TGF- $\beta$ 1 antibody, the antisense and ribozyme to TGF- $\beta$ 1, decorin, IFN- $\gamma$  and - $\alpha$ , or relaxin—the ability of suramin to neutralize the fibrotic effect of TGF- $\beta$ 1 and enhance muscle regeneration makes this molecule particularly well-suited for use in applications to improve muscle healing after injury. In addition, the fact that suramin is already approved by the FDA for use in humans makes this molecule an ideal candidate for use in clinical applications to improve muscle healing in soldiers. Using an animal model of muscle contusion, a common military injury, we will determine the appropriate dose and time of administration of suramin (**Technical Objective 1**). Better characterization of the mechanisms by which suramin enhances muscle regeneration is extremely important because an improved understanding of these mechanisms may reveal novel ways to promote muscle growth and regeneration (**Technical Objective 2A**). We also will investigate suramin's interaction with myostatin and follistatin, 2 important regulators of muscle growth (**Technical Objective 2B**). In summary, the studies proposed in this application will enable us to determine whether suramin, a drug already approved by the FDA, can improve muscle healing by preventing scar tissue formation after a common military injury (muscle contusion); we also will examine the mechanism(s) by which suramin promotes muscle regeneration. The results of these studies could aid in the development of innovative therapies to promote healing in muscles damaged by different types of injury or disease (e.g., muscular dystrophies), therapeutic approaches that could easily be translated from animal experiments to human clinical applications.

The overall goals of the proposed project are as follows: (i) demonstrate that suramin can improve muscle healing in a dose- and time-dependent manner by preventing scar tissue formation

after muscle contusion (a common military injury); (ii) determine the mechanisms by which suramin enhances muscle healing after injury. We will investigate whether the enhanced muscle healing observed after suramin treatment is due solely to its inhibition of TGF- $\beta$ 1 activity (**Technical Objective 1**) or to suramin's promotion of muscle regeneration through potential interactions with muscle growth regulators, particularly its possible down-regulation of myostatin or up-regulation of follistatin (**Technical Objectives 2A and 2B**).

## **2) Supplemental Proposal 1**

**New Technical Objective 1:** To determine the pharmacokinetics of suramin delivery when administered via intramuscular injection in mice for the treatment of skeletal muscle injuries.

Our laboratory has shown that intramuscular (IM) injection of suramin after laceration and strain injuries decreases skeletal muscle fibrosis in mice and improves muscle healing, resulting in a near complete recovery of muscle function (Chan et al, 2002; Chan et al, 2003). The clinical availability of suramin makes this agent particularly appealing for its use in the treatment of muscle injuries in humans. However, to date, clinical investigations of the use of suramin have been primarily limited to intravenous administrations, which is complicated by a narrow therapeutic index, and dose-limiting toxicities. The dose-limiting toxicities are related to suramin plasma concentrations, of which acceptable levels and durations for humans have been previously reported (Eisenberger et al, 2005). With this in mind, we will perform pre-clinical pharmacokinetic studies in mice to evaluate the concentration/ time data of suramin when administered intramuscularly. Specifically, we will perform measures of therapeutic dosing, half-life and clearance calculations, which will then be used as a guide for the design of phase 1 clinical trials.

**New technical objective 2:** To evaluate the beneficial effect of decorin, another antifibrosis agent, on muscle regeneration and healing and its mechanism of action.

As mentioned above, various reports indicate that the overproduction of TGF- $\beta$ 1 in response to injury and disease is a major cause of tissue fibrosis in animals and humans. We have observed that TGF- $\beta$ 1 plays a central role in skeletal muscle fibrosis and that the use of antifibrosis agents to inactivate this molecule can reduce muscle fibrosis and consequently significantly improve muscle healing after injury. Although the effect of TGF- $\beta$ 1 can be blocked by various approaches—including treatment with a neutralizing TGF- $\beta$ 1 antibody, the antisense and ribozyme to TGF- $\beta$ 1, suramin [The focus of the last year research proposal ], relaxin, and IFN- $\gamma$  —the unique ability of decorin to neutralize the fibrotic effect of TGF- $\beta$ 1 and independently enhance muscle regeneration makes this molecule particularly well-suited for use in applications to improve muscle healing after injury. Our preliminary data demonstrate that the stimulation of myogenic cells (C2C12 cells) with decorin enhances myogenic differentiation in vitro. Similarly, C2C12 cells genetically engineered to express decorin display an enhanced ability to undergo myogenic differentiation in vitro and in vivo. We also have observed that direct gene transfer of decorin by injection into uninjured skeletal muscle can decrease the fibrosis and enhance the muscle regeneration observed after subsequent injury of that muscle. These results suggest that decorin may independently enhance muscle regeneration and impede fibrosis. On the basis of our prior and preliminary findings, we propose to validate the beneficial effect of decorin on muscle regeneration by conducting gain- and loss-of-function experiments.

## **3) Supplemental Proposal 2**

**Additional Technical Objective #1:** To evaluate whether decorin's beneficial effect on muscle healing is mediated through its influence on muscle inflammation.

*Hypothesis:* Decorin improves muscle healing by influencing muscle inflammation.

It has been observed that decorin influences the differentiation, survival, and infiltration of macrophages. We, therefore, propose experiments designed to reveal the role of decorin on the inflammatory phase of muscle healing. To determine the influence of decorin on the infiltration of inflammatory cells (macrophages and



neutrophils) within the injured skeletal muscle, we will conduct gain- and loss-of-function experiments involving the injured skeletal muscles of decorin<sup>-/-</sup> mice, decorin-over-expressing mice (after AAV gene transfer of decorin), and normal WT mice as described above. To conduct the gain-of-function experiments, we will use gene therapy (adeno-associated viral [AAV] gene transfer in collaboration with Dr. Bing Wang; Vector Core) to deliver decorin into lacerated skeletal muscle (decorin-expressing mice). We will use decorin<sup>-/-</sup> knockout mice (provided by Dr. Renato V. Iozzo) to perform the loss-of-function experiments. If decorin is observed to have an effect on inflammatory cells, we will subsequently determine whether the COX-2-dependent prostaglandins (PGs) are also modulated by decorin since it has been shown by our laboratory as well as others that the COX-2 pathway is essential during the early stage of skeletal muscle regeneration. If the COX-2 pathway is influenced, at least in part, by decorin, we will use COX-2 deficient mice, as well as clodronate liposomes to deplete macrophages and determine whether the beneficial effect of decorin on muscle healing is related to decorin's effect on muscle inflammation.

**Additional Technical Objective #2:** To investigate whether decorin's beneficial effect on muscle healing is mediated through MSTN or FLST, two important regulators of muscle growth.

Hypothesis: Decorin promotes muscle healing by down-regulating MSTN or up-regulating FLST.

The first set of experiments will enable us to determine whether differences exist among the levels of MSTN and FLST expression in the injured skeletal muscles of decorin<sup>-/-</sup> mice, decorin-overexpressing mice (mice with their skeletal muscle transduced with AAV-decorin), and normal wild-type (WT) mice. We will measure the levels of MSTN and FLST expression in the injured skeletal muscle at different times after injury. We will compare the results in the lacerated muscle of normal WT mice with those obtained from the lacerated muscle of decorin<sup>-/-</sup> mice and mice whose muscles overexpress decorin. The observation that the level of MSTN and FLST expression in injured skeletal muscle differs between these different mice (decorin<sup>-/-</sup>, decorin<sup>++</sup>, and normal mice) will support the hypothesis that decorin interacts with MSTN or FLST.

The second set of experiments will evaluate the effect of decorin on the healing of lacerated muscles in myostatin-overexpressing mice, which typically display lower muscle mass and reduced muscle size relative to normal WT mice [66]. We will compare the results with those observed in the lacerated muscles of MSTN<sup>-/-</sup> mice and normal mice treated with decorin. We then will measure the level of muscle regeneration and healing at different times after injection. A reduction in the beneficial effect of decorin on muscle healing in the MSTN<sup>++</sup> mice, when compared to the injection of decorin in normal and MSTN<sup>-/-</sup> mice, will support our preliminary findings that MSTN interferes with the beneficial effect of decorin in muscle regeneration.

In a third set of experiments, we are proposing to investigate whether the detrimental effect of MSTN observed in normal mice is influenced by decorin expression. We will evaluate the effect of MSTN on the healing of lacerated muscles in decorin-overexpressing mice (after AAV gene transfer of decorin). We will compare the results with those observed in the MSTN-treated lacerated muscles of decorin<sup>-/-</sup> mice and normal WT mice. We then will measure the level of muscle regeneration and healing at different times after injection. We will compare the results with the healing observed in the lacerated muscle of decorin<sup>-/-</sup> mice and normal muscle treated with the same dose of MSTN. A reduction on the detrimental effect of MSTN on muscle healing in the decorin<sup>++</sup> mice, when compared to the decorin<sup>-/-</sup> and normal muscle, will support our preliminary findings that decorin interferes with the deleterious effect of MSTN in skeletal muscle.

We anticipate that the beneficial effect of decorin on muscle healing will be influenced by the level of MSTN expression and will be significantly reduced in the MSTN<sup>++</sup> mice. Similarly, the detrimental effect of MSTN on muscle healing will also be influenced by the level of decorin expression and will be significantly reduced in the decorin over-expressing mice. We alternatively propose a *final set of experiments* to determine whether decorin interacts either directly with MSTN or potentially through an intermediate molecule such as FLST, another muscle regulator. In fact, research has shown that mice overexpressing FLST display a dramatic increase in muscle mass, and that FLST antagonizes MSTN by a direct protein interaction. Indeed, our preliminary results show that FLST-treated muscle cells differentiate into myotubes that are significantly larger than those formed by nontreated cells,

and decorin up-regulates the expression of FLST in muscle cells *in vitro*. These results support the hypothesis that decorin's beneficial effect on muscle healing is related to the up-regulation of FLST. Therefore, we will examine the effect of FLST on muscle regeneration and healing after laceration injury in decorin<sup>++</sup> mice (after AAV decorin gene transfer) and compare the results with those observed in normal WT mice and decorin<sup>-/-</sup> mice. We then will measure the level of muscle regeneration and healing at different times after injection, and compare the results among the different groups at different times after injury. A reduction in the beneficial effect of FLST on muscle healing in the decorin<sup>-/-</sup> mice, when compared to the WT and decorin<sup>++</sup> mice, will support our preliminary findings that decorin also interacts with FLST. These results, in combination with the fact that decorin up-regulates the expression of FLST in muscle cells *in vitro*, will support the contention that decorin improves muscle healing through a potential up-regulation of FLST which will consequently antagonize the effect of myostatin.

**Additional Technical Objective #3:** To evaluate whether angiotensin II receptor blockade after injury represents a potential non-invasive approach to improve muscle regeneration and repair after military-related muscle injury

**Hypothesis:** Angiotensin II receptor blockade will improve muscle healing after injury.

In our laboratory, we have investigated several biological agents, which have proven to be of some benefit in altering the natural course of muscle injury. Specifically, we have focused our recent efforts on agents that inhibit muscle fibrosis via inhibition of TGF- $\beta$ 1, a key cytokine in the fibrotic signaling pathway in skeletal muscle. Using decorin, suramin, relaxin, and gamma interferon, we have demonstrated that these therapies can decrease fibrosis and increase regeneration following skeletal muscle injury. However, their use clinically is hampered by relatively severe side-effect profiles, lack of oral dosing formulations, and, in the case of decorin, lack of FDA approval for use in humans. These limitations are under investigation as part of our current line of funding from the Department of Defense (DOD).

Fibrosis is a pathological process that is not unique to the skeletal muscle system. Observations have linked pathologic fibrosis in various organ systems to the local effects of a naturally-occurring molecule, angiotensin II, an end-product of the blood pressure-regulating renin-angiotensin system. The modulation of angiotensin II with angiotensin converting enzyme inhibitors or angiotensin II receptor blockers has demonstrated decreased fibrosis and improved function in liver, kidney, and lung tissue. Injured cardiac muscle in disease entities such as congestive heart failure also demonstrates dysfunction related to fibrosis. Myocardium exposed to decreased levels of angiotensin II, either through the use of angiotensin converting enzyme inhibitors or angiotensin receptor blockers, has also demonstrated measurably improved function. Investigators have also observed a relationship between the modulation of angiotensin II and skeletal muscle. Patients treated with angiotensin-modulating medications for hypertension also displayed the unexpected side-effect of decreased rates of muscle wasting and a reduction in the relative amount of adipose tissue within their musculature. Moreover, elite athletes, particularly those in endurance sports, have inherent differences in their body's metabolism of angiotensin II as decreased exposure resulted in improved skeletal muscle function.

Recent experiments have been performed to elucidate the mechanism by which angiotensin II receptor blockade modulates TGF- $\beta$ 1, which has also been implicated in the prevention of muscle regeneration in murine models of chronic myopathic disease. We then hypothesized that systemic delivery of an angiotensin II receptor blocker may enhance muscle regeneration and decrease fibrosis in a laceration model of skeletal muscle injury. To test this hypothesis, we performed a set of experiments where forty mice underwent bilateral partial gastrocnemius lacerations. Mice were assigned randomly to a control group (tap water), a low-dose angiotensin receptor blocker (Losartan, Merck) group (30 mg/Kg/day), or a high-dose angiotensin receptor blocker group (300 mg/Kg/day). Mice were sacrificed 3 or 5 weeks after injury, and the lacerated muscles were examined histologically for myofiber regeneration and fibrosis. *In vitro* experiments measured the production of TGF- $\beta$ 1 induced by angiotensin II in a cell line of fibroblasts through ELISA and western blot. A second set of experiments were performed for physiological testing to establish the peak force and torque generated by the recovering muscle in each group.

Our results indicated that angiotensin II induced the expression of TGF- $\beta$ 1 in fibroblasts. Compared with control mice at 3 and 5 weeks, Losartan-treated mice (both low and high-dose groups) exhibited a significant and dose-dependent improvement in muscle regeneration and a measurable reduction in scar tissue formation within the area of injury. The treatment groups showed a trend toward functional improvement after five weeks of therapy.

These results indicate that by modulating the response to local and systemic angiotensin II, angiotensin receptor blocker therapy significantly reduced fibrosis and led to an increase in the number of regenerating myofibers in acutely injured skeletal muscle. These effects were apparent as early as 3 weeks after injury in mice treated with one-tenth of the anti-hypertensive dose of angiotensin receptor blocker used clinically. The clinical implications for this application of angiotensin receptor blockers are potentially far-reaching and include not only sports and military-related injuries, but also diseases like the muscular dystrophies. We believe that this treatment could be effective when instituting a non-invasive treatment after the injury has taken place, a more clinically relevant scenario in treating muscle injuries.

## **B) Results**

### **1) Results of Original Technical Objectives:**

It was unknown whether suramin could improve muscle healing after contusion injury, the most commonly encountered muscle injury. Past studies had been performed on mice that had received laceration and strain injuries. It also remains unclear whether this enhanced muscle regeneration is a direct effect of suramin. We have performed studies during the first year of funding to examine whether suramin would promote differentiation of myogenic cells *in vitro* and improve injured muscle healing by enhancing regeneration and reducing fibrosis *in vivo*, by using an animal model of muscle contusion.

*Muscle-derived stem cell differentiation assay:* Muscle-derived stem cells (MDSCs) were isolated from wild type mice (C57BL/6J) via the modified preplate technique. MDSCs ( $10^4$  cells/well) were seeded into 12-well plates and cultured in Dulbecco's modified Eagle's medium (DMEM) containing 10% fetal bovine serum, 10% horse serum, 0.5% chicken embryo extract, and 1% penicillin/streptomycin. After 24 hours, the medium was replaced with differentiation medium (DMEM containing 2% horse serum and 1% penicillin/streptomycin) containing different concentrations of suramin (0, 1, 10, and 100  $\mu$ L/mL). After another 24 hours, the medium was replaced with differentiation medium. All cells were grown at 37°C in 5% CO<sub>2</sub>. Three days after incubation, the fusion index was assessed by counting the number of nuclei in differentiated myotubes as a percentage of the total number of nuclei.

*Immunocytochemistry in vitro:* Immunocytochemistry was performed on the cells *in vitro* to examine their expression of fast myosin heavy chain (MyHC).

*Animal model:* The muscle contusion model was developed in normal wild-type mice (7 to 10 weeks of age, with an average weight of 24.0g). A 17g stainless steel ball was dropped through an impactor from a height of 100 cm onto the animal's tibialis anterior (TA) muscle. Mice were divided into 4 groups (5 mice/group). Different concentrations of suramin (0, 2.5, 5, and 10 mg in 20  $\mu$ L of phosphate-buffered saline [PBS]) were injected intramuscularly two weeks after injury. Statistical analysis was performed with ANOVA.

*Suramin stimulates MDSC differentiation:* Suramin treatment promoted the differentiation of MDSCs *in vitro* in a dose-dependent manner. We observed a significantly higher fusion index in each of the two suramin treatment groups (10 and 100  $\mu$ g/mL) than in the control group (0  $\mu$ g/mL). Furthermore, 100  $\mu$ g/mL of suramin treatment enhanced the differentiation significantly more than the other suramin treatments (1 and 10  $\mu$ g/mL).

*Suramin enhances muscle regeneration and decreases fibrosis after contusion injury*: We observed a significant increase in the number of regenerating myofibers in all of suramin treated groups (2.5, 5, and 10 mg/20  $\mu$ L PBS) when compared with the control group (0mg/20 $\mu$ L of PBS).

Moreover, Masson's trichrome staining showed significantly less fibrotic area in all of suramin treated groups than in the control group. Although all three suramin treated groups showed significant improvement in healing by way of muscle regeneration and fibrosis inhibition, there was no significant difference between the three suramin treatment groups.

This data indicate that the suramin-treated MDSC groups have higher fusion indices than the control group *in vitro*. This suggests that suramin can enhance the differentiation of MDSCs, and reveals a portion of the mechanism by which suramin enhances muscle regeneration following injury. This is the first study to show that suramin not only has antiproliferative effects on fibroblasts, it affects the differentiation of MDSCs directly. Our results clearly indicate that suramin can enhance muscle regeneration and prevent fibrosis after a contusion injury, the most common muscle injury (**Refer to Appendices 1, 7 and 8**). Our future study will investigate the mechanism(s) by which suramin enhances the differentiation of myogenic cells.

We have recently furthered these findings by performing a series of experiments to determine the mechanism (s) behind the beneficial effect of suramin on muscle healing after injury. Our hypothesis was that suramin enhances muscle healing by both stimulating muscle regeneration and preventing fibrosis in contused skeletal muscle. *In vitro*: Myoblasts (C2C12 cells) and muscle-derived stem cells (MDSCs) were cultured with suramin and the potential of suramin to induce their differentiation was evaluated. Furthermore, MDSCs were co-cultured with suramin and myostatin (MSTN) to monitor the capability of suramin to neutralize the effect of MSTN. *In vivo*: Varying concentrations of suramin were injected in the tibialis anterior muscle of mice two weeks after muscle contusion injury. Muscle regeneration and scar tissue formation were evaluated by histological analysis and functional recovery was measured by physiological testing. Our results demonstrated that suramin stimulated the differentiation of myoblasts and MDSCs in a dose-dependent manner. Moreover, suramin neutralized the inhibitory effect of MSTN on MDSC differentiation. *In vivo*, suramin treatment significantly promoted muscle regeneration, decreased fibrosis formation, reduced myostatin expression in injured muscle, and increased muscle strength after contusion injury.

In conclusion our results indicate that intramuscular injection of suramin following a contusion injury improved overall skeletal muscle healing. Suramin enhanced myoblast and MDSC differentiation and neutralized MSTN's negative effect on myogenic differentiation *in vitro*, which suggests a possible mechanism for the beneficial effects that this pharmacological agent exhibits *in vivo*. We believe that these findings could contribute to the development of biological treatments to aid in muscle healing after experiencing a muscle injury. These results were recently published in the American Journal of Sports Medicine (**refer to Appendix 8**).

In a final set of experiments, we have examined whether suramin treatment enhances muscle regeneration and reduce fibrosis by down-regulating myostatin expression *in vivo*. The muscle contusion was made on the tibialis anterior (TA) muscle of each mouse. Two weeks after injury, different concentrations of suramin (0 and 2.5 mg) were injected intramuscularly (n=20 mice/ group). At different time points (0.5, 1, 2, 10, and 14 days after injection), mice were sacrificed and cryosections of TA muscle were analyzed histologically. Suramin (2.5 mg) injection demonstrated a significant increase in the number of regenerating myofibers and reduction of fibrotic area when compared with the control group (0 mg). Furthermore, suramin injection effectively inhibited the expression of myostatin in the injured muscle. Our results suggest that suramin improves skeletal muscle healing by enhancing regeneration and reducing fibrosis after contusion injury through a potential decrease in myostatin expression in the injured skeletal muscle. Our findings may contribute to the development of progressive therapies for muscle injury. (**Refer to Appendices 1, 7 and 8**)

## 2) Results of Supplemental Proposals 1 and 2:

We have shown that decorin, a small leucine-rich proteoglycan, can inhibit TGF- $\beta$ 1 to prevent fibrous scar formation and improve muscle healing after injury. In the decorin-treated muscle, an enhancement of muscle regeneration is observed through histological examination. We have recently determined whether decorin has a direct effect on myogenic cells' differentiation. Our results indicate that myoblasts genetically engineered to express decorin (CD cells) differentiated into myotubes at a significantly higher rate than did control myoblasts (C2C12). This enhanced differentiation led to the up-regulation of myogenic genes (*Myf5*, *Myf6*, *MyoD*, and *myogenin*) in CD cells *in vitro*. We speculate that the higher rate of differentiation exhibited by the CD cells is due to the up-regulation of follistatin, PGC-1 $\alpha$ , p21, and the myogenic genes, and the down-regulation of TGF- $\beta$ 1 and myostatin. Decorin gene transfer *in vivo* promoted skeletal muscle regeneration and accelerated muscle healing after injury. These results suggest that decorin not only prevents fibrosis, but also improves muscle regeneration and repair.

Recent studies have shown that myostatin (MSTN), first identified as a negative regulator of skeletal muscle growth, may also be involved in the formation of fibrosis within skeletal muscle. In a recent study, we further explored the potential fibrotic role of MSTN, as well as its interactions with both transforming growth factor-beta1 (TGF- $\beta$ 1) and decorin. We discovered that MSTN stimulated fibroblast proliferation *in vitro*, and induced its differentiation into myofibroblasts. We further found that, while TGF- $\beta$ 1 stimulated MSTN expression, MSTN stimulated TGF- $\beta$ 1 secretion in C2C12 myoblasts. Decorin, a small leucine-rich proteoglycan, was found to neutralize the effects of MSTN in both fibroblasts and myoblasts, and up-regulate follistatin (FSTN), an antagonist of MSTN. Moreover, FSTN, an antagonist of MSTN, was up-regulated by decorin. The results of *in vivo* experiments showed that MSTN-knockout mice developed significantly less fibrosis and displayed better skeletal muscle regeneration when compared to wild-type mice at 2 and 4 weeks following laceration injury. In wild-type mice, we found that MSTN stimulated myofibers to express TGF- $\beta$ 1 in skeletal muscles at early time points following injection. Both TGF- $\beta$ 1 and MSTN were additionally seen to co-localize in myofibers in the early stages of injury. In summary, these findings define a fibrogenic property of MSTN, and indicate a coregulatory relationship between TGF- $\beta$ 1, MSTN, and decorin. Please refer to the references listed below in the Reportable Outcomes Section to access these results. The complete recovery of injured skeletal muscle has posed a constant challenge for orthopaedic physician. Once injured, skeletal muscle is able to undergo regeneration from satellite cells; nevertheless, in the serious injured muscle, the formation of fibrosis often impedes effective muscle regeneration and resulted in an incomplete muscle healing. Therefore, to develop biological approaches to improve muscle healing, it is crucial to better understand the mechanisms of the skeletal muscle fibrosis. In the current studies, we found that myostatin (MSTN), a member of TGF- $\beta$  family, plays a role in the formation of skeletal muscle fibrosis, besides the other putative fibrosis stimulator, TGF- $\beta$ 1. *In vitro*, MSTN directly stimulated the proliferation of fibroblasts and their productions of fibrotic proteins. *In vivo*, after laceration injury, gastrocnemius muscles of MSTN<sup>-/-</sup> mice showed less fibrosis and better muscle regeneration than wide-type (WT) counterparts. Considering MSTN as a therapeutic target of skeletal muscle healing, we found that inhibitors of MSTN, MSTN propeptide (MPRO) and follistatin, effectively blocked MSTN signaling and improved skeletal muscle healing after injured. We used adeno-associated virus (AAV)-mediated MPRO cDNA to successfully deliver MPRO *in vivo* and improve skeletal muscle healing of normal mice after laceration, and ameliorate dystrophic pathology of *mdx*/SCID mice. Furthermore, our results demonstrated FLST overexpression (FLST/OE) mice exhibited decreased fibrosis and increased muscle regeneration in injured skeletal muscle as compared to wild-type (WT) mice. Moreover, muscle progenitor cells (MPCs) isolated from MSTN<sup>-/-</sup> and FLST/OE mice significantly regenerated more myofibers than MPCs obtained from WT mice, when transplanted into dystrophic muscles. Collectively, our results suggested that MSTN directly stimulated fibrosis in the injured skeletal muscle; blocking MSTN signaling with MPRO or FLST improved skeletal muscle healing after laceration injury; blocking MSTN signaling in donor MPCs significantly enhanced the success of cell transplantation into dystrophic muscles. Our

studies not only uncover some of the mechanisms implicated in skeletal muscle fibrosis and regeneration, and help the development of new therapeutic approach for promoting the healing of injured or diseased skeletal muscle, but also render a new sight of how to obtain robust genetically modified cell populations for cell therapy. **(Refer to Appendices 2, 3 and 4)**

Muscle injuries are very common musculoskeletal problems encountered in sports medicine. Although these injuries are capable of healing, complete functional recovery is hindered by the formation of dense scar tissue triggered by TGF- $\beta$ 1. We have previously reported that several agents such as decorin and suramin can inhibit fibrosis and improve regeneration in injured skeletal muscle. The safety of these agents, however, remains unknowns to use those agents for treating muscle injury. By contrast, Losartan (LOS), one of the Angiotensin II Receptor Blockers (ARBs)—is a FDA approved antihypertensive medication and has been shown to also be antifibrotic in a variety of tissues, including skeletal muscle. This ARB has a well-tolerated side-effect profile, can also block TGF- $\beta$ 1 to attenuate the development of pathological fibrosis. In this study, we investigated optimum dose of LOS in treating injured muscle to help the translation of this research from bench to bedside.

The biphasic effect of LOS on C2C12 myoblasts *in vitro*, stimulating at low dose while decreasing at high dose, suggested that there is an optimal dose of LOS. Consequently, we found that LOS improves skeletal muscle regeneration at 4 weeks after contusion injury, except that these effects were reduce/eliminated in 1000 mg/kg/day group. The best effective dose was 300 mg/kg/day. Overall, these effects of LOS were more pronounced for regeneration than for fibrosis. These *in vivo* results are consistent with our *in vitro* results that LOS was able to exert effects on C2C12 whereas fibroblasts were not affected by either ANG or LOS. Regeneration and fibrosis are two competitive processes after muscle injury; therefore, decreasing fibrosis observed in LOS-treated group is can be the result of the increase regeneration. In other words, LOS might indirectly reduced fibrosis by directly stimulating regeneration. Although there were not statistical differences in fibrosis in lower dose LOS groups (3 and 30 mg/kg/day) as compared to control, these effects of LOS on both regeneration and fibrosis showed similar dose dependent trend. However, *in vivo* results above were obtained only from single time point after injury. Since there are time lags between peaks of myofiber regeneration and fibrosis after injury, further investigations are required to examine the effect of LOS on regeneration and fibrosis at their individual peak time, which will facilitate clinical application of ARBs in improving skeletal muscle healing. **(Refer to Appendices 9, 12 and 14).**

Members of our clinical team in Orthopaedic surgery brought the use of Losartin to clinic and successfully treated a 21 year old man who had experienced a recurrent hamstring strain. After obtaining the subject's informed consent for treatment, he was started on a 30-day treatment course of losartan at the manufacturer's recommended dose of 50 mg per day by mouth. The subject underwent a routine rehabilitation supervised by his athletic trainer along with the pharmaceutical treatment, gradually progressing to eccentric strengthening. He was followed every 7-10 days with serial measurement of hamstring flexibility and strength. The subject reported no side effects while he was taking the study medication and remained normotensive throughout. Eleven weeks after the injury, an isokinetic test of the hamstrings was performed showing an essentially normal result. In summary, all isokinetic testing parameters were within a normal range compared to the contralateral leg. **(Refer to Appendix 14)**

We have previously reported that Losartan (LOS), one of the Angiotensin II Receptor Blockers (ARBs), which is FDA approved for antihypertensive treatment, has been shown to improve muscle healing through antifibrotic action [Bedair HS, *et al.*, *Am J Sport Med.* 2008; 36: 1548-54]. We also demonstrated that specific doses of LOS (30 mg/kg/day and higher) improved muscle regeneration and attenuated the development of pathological fibrosis when it was administrated immediately after injury [Uehara K, *et al.*, 55th Annual Meeting of the Orthopaedic Research Society, 2009]. In this study, we investigated whether LOS could improve muscle strength recovery after contusion injury, and also attempted to understand the mechanism of LOS action by

analyzing gene expression of myostatin and follistatin, which are considered important regulators of skeletal muscle growth. LOS improved TA muscle force recovery after contusion injury. Specific peak twitch force and tetanic force was elevated in mice receiving high dose of LOS (30 and 300 mg/kg/day) in comparison to the animals receiving low dose of LOS (3 and 10 mg/kg/day). Expression of myostatin in the injured TA muscle in the control-injury and low dose of LOS treatment groups was lower than in the normal TA muscle, while there was no difference between normal and high dose of LOS treatment groups. Expression of follistatin in the control group was higher than in normal muscle and low dose of LOS treatment groups. The highest expression of follistatin was observed in the 30 mg/kg/day of LOS treatment group and it was significantly higher compared to the control group. Functional recovery is the most important factor in the skeletal muscle healing after injury. Here we demonstrate that LOS administration immediately after injury improves recovery of skeletal muscle strength. These results also support our previous histological findings [Uehara K, *et al.*, 55th Annual Meeting of the Orthopaedic Research Society, 2009]. We believe that the mechanism of muscle regeneration after injury might be related to the expression of follistatin, positive regulator of skeletal muscle growth. We noticed over expression of follistatin in the 30 mg/kg/day treatment group compared to the normal and control-injury groups. These findings correlate with the results of physiological testing. It is unclear why the 30 mg/kg/day LOS displayed an increased expression of myostatin which is a negative regulator of skeletal muscle growth. Our results suggest that continuous administration of the high dose of LOS, in particularly 30 mg/kg/day, immediately after skeletal muscle injury could accelerate skeletal muscle functional recovery. We aimed to evaluate only a single time point of LOS administration immediately after injury. Further studies are required to determine the biological effect of LOS and facilitate the clinical application of ARBs for improvement of skeletal muscle healing. **(Appendix 15)**

Our previous study revealed that 30 mg/kg/day of LOS treatment was effective in promoting muscle healing and inducing an antifibrotic effect in a murine model of skeletal muscle after injury. However, the effective dose (30 mg/kg/day) which was administered immediately after muscle injury is higher compared to the dose used in humans (10 mg/kg/day). In this study we investigated the effect of muscle healing in a murine animal model using the recommended human dose of LOS (10 mg/kg/day) administered at different time points after injury. We observed significant increases in the number of centronucleated myofibers in the day 3 treatment group when compared with other treatment groups. The highest effect on muscle regeneration coincided with significant decrease of fibrosis in the day 3 treatment group. LOS improved muscle strength recovery after contusion injury. Specific peak twitch force and peak tetanic force was significantly greater in mice treated with LOS beginning at day 3 after injury. Expression of FSTN detected by RT-PCR in the day 3 and day 14 LOS treatment groups was greater than in the normal non-injured or LOS treated at day 0 and day 7 groups. Expression of MSTN in the day 3, day 7 and day 14 LOS treatment groups was lower than in the normal, control and day 0 LOS treatment groups. The highest expression of FSTN coincided with the lowest expression of MSTN in the day 3 LOS treatment group. This study revealed that the most effective timing for administration of human dose of LOS (10 mg/kg/day) was 3 days after muscle injury. We observed an increased number of centronucleated myofibers and decreased area of fibrosis when LOS was administered at day 3 after injury. The functional recovery after skeletal muscle injury is the most important factor for clinical translation of this therapy. We demonstrate that an enhancement of muscle strength in the day 3 LOS treatment group correlates with the improvement of muscle regeneration and the reduction of fibrosis. We have previously reported that muscle regeneration and fibrosis formation are two concomitant processes after muscle injury, and the effect of LOS was more prominent on muscle regeneration than on fibrosis. This current study supports this finding. In addition, it may suggest that the administration of LOS effectively leads to enhanced muscle regeneration after muscle injury via the down regulation of endogenous MSTN, which is a negative regulator of skeletal muscle growth. A decrease in FSTN expression was also observed in the day 3 LOS treatment group which may be related to the decrease in MSTN expression. In summary, we indicate that 10 mg/kg/day (human safety dose) of LOS treatment initiated at 3 days after contusion injury can enhance structural and functional healing in mouse skeletal muscle. **(Appendix 16).**

The Department of Orthopaedic Surgery at the University of Pittsburgh initiated the use of Losartan in two case studies of young athletes that presented with recurrent hamstring injuries. Note that these studies are only provided as translational evidence of the research being performed at the SCRC. These clinical trials were funded by the department of Orthopaedic Surgery at the University of Pittsburgh. Losartan was given to the patient volunteers as an off label use of the drug. No DOD funding was used for these studies. Given that Losartan has already been used clinically with an extremely safe side effect profile, physicians at the University of Pittsburgh's Department of Orthopaedic Surgery have conducted two case studies in young college athletes that sustained recurrent hamstring injuries and whose recoveries were safely improved with losartan. This is an off-label use of losartan (i.e.: the FDA has not approved labeling the device for the described purpose). Here we report the results obtained. Subject #1 was a, 21 year old male college athlete (football punter). He presented 10 days after an acute onset of "searing" pain in his left posterior thigh when he was kicking with his left leg. He referred a similar injury 5 weeks prior to the present injury. The 2<sup>nd</sup> subject was a 22 years old male,, college athlete (Ultimate Frisbee). He presented 4 days after an acute onset of pain in his left posterior thigh while he was sprinting. He referred two previous hamstring injuries (2 and 7 months prior to the present injury). ***MRI results (at time of injury):*** Subject #1: Acute Grade 2 hamstring strain was observed with a partial thickness tear of the biceps femoris at the proximal myotendinous junction with surrounding edema without an associated avulsion fracture or hematoma. Subject #2: Grade 2 strain with partial thickness tear of the left biceps femoris at the mid aspect, extends approximately 6 cm in the craniocaudal dimension. ***Hamstring flexibility and strength:*** Subject #1: By the third week after the injury, no deficit was evident in hamstring flexibility. By the ninth week, the isometric hamstring strength measurements at 30 and 90 degrees of knee flexion were 92 and 84% than the uninjured side respectively (Fig.1). Subject #2: Also, by the third week after the injury, no deficit was evident in hamstring flexibility. By the ninth week, the injured side had a higher isometric hamstring strength measurement at 30 and 90 degrees of knee flexion. They were 132% and 110% than the uninjured side respectively. We have described use of losartan, which is an FDA-approved angiotensin II receptor blocker, to treat two healthy collegiate athletes with a grade 2 biceps femoris injury. The patients tolerated the course of losartan well with no hypotension or any other side effects. Additionally, the patients demonstrated recovery of normal flexibility and strength compared to the contra-lateral leg. Both subjects were ready for return to sports in 9 to 11 weeks after injury. (**Appendix 17**)

### 3) Current Results:

#### a) The Effect of Timing of Administration of Losartan on Skeletal Muscle Healing After Traumatic Injury

In this study we investigated the effect of LOS at the dosage clinically used in humans (10 mg/kg/day) when administered at different time points after contusion injury.

***Animal model:*** A muscle contusion injury was created in the tibialis anterior (TA) muscle of C57BL/6J wild-type mice. The administration of 10 mg/kg/day of LOS (40mg/L) was initiated on days 0, 3, 7 or 14 after injury and continued for 1 or 4 weeks. Tap water not supplemented with LOS was administered to the animals in the untreated injury control group, and in the non-injury group (normal group) (6 mice in each group). The LOS dosing was calculated based on the average fluid intake of the mice. Four weeks after injury, we performed physiological testing and harvested the TA muscles for histology. The dose of LOS at 10 mg/kg/day is equivalent to the clinical dose used to treat humans with high blood pressure (50 mg/day) (4).

***Physiological testing:*** Four weeks after injury, we performed physiological testing. Under general anesthesia, the peroneal nerve was exposed by a lateral incision at the knee which was then hooked to a small electrode. To stabilize the hind limb, the knee and foot was secured to the platform with cloth tape. The foot was tied securely to the lever arm of 1500A Small Intact Muscle Test System (Aurora Scientific Inc., ON, Canada). The system

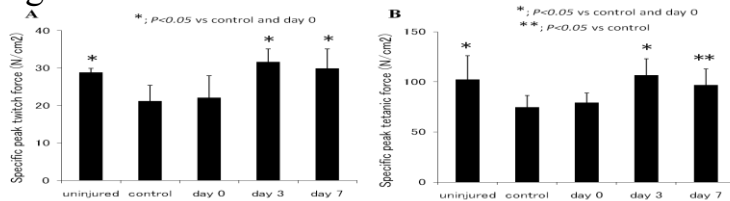


has Dynamic Muscle Control Software (Aurora Scientific Inc.) to monitor muscle force. All data were displayed and stored on a computer and analyzed with the Dynamic Muscle Analysis Software (Aurora Scientific Inc.).

**Histology:** TA muscles harvested 4 weeks after injury were cryosectioned and stained for hematoxylin and eosin (H&E) and Masson's trichrome stain. The number of centronucleated regenerating myofibers was counted to evaluate muscle regeneration. Northern Eclipse software (Empix Image, Inc.) was used to analyze the total cross-sectional area of muscle fibrosis.

**Evaluation of Myostatin and Follistatin:** TA muscles harvested 1 week after injury were prepared for western blot analysis to determine the levels of MSTN and FSTN expression.

**Figure 1**



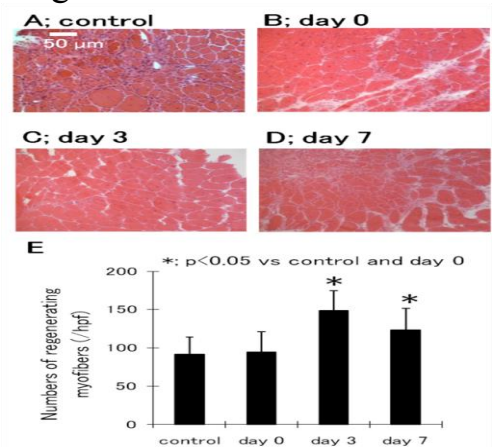
**Statistical analysis:** Significant differences were established by ANOVA followed by Scheffe's post hoc test. Statistical significance was defined as  $p < 0.05$ .

**Losartan Improved Muscle Strength Recovery after Contusion Injury:** Results from the physiological evaluations performed at 4 weeks

post-injury (Figure 1A-B). Specific peak twitch and tetanic forces were significantly greater in mice where LOS treatment was initiated 3 days ( $31.70 \pm 3.42$ ,  $106.6 \pm 16.4 \text{ N/cm}^2$ ) after injury compared to the other groups (peak twitch  $21.21 \pm 4.22$ ,  $22.13 \pm 5.83$ , and peak tetanic  $74.81 \pm 11.7$ ,  $79.22 \pm 9.12 \text{ N/cm}^2$ ,  $p < 0.05$  respectively). The specific peak twitch and tetanic forces of the uninjured group (peak twitch;  $28.85 \pm 1.09$ , peak tetanic;  $102.3 \pm 23.8 \text{ N/cm}^2$ ) was significantly greater than the control and day 0 groups. The specific peak twitch and tetanic forces of the day 7 group (peak twitch;  $29.99 \pm 5.18$ , peak tetanic;  $96.96 \pm 15.9 \text{ N/cm}^2$ ) was significantly greater than the control and day 0 groups ( $p < 0.05$  respectively, Figure 1A-B). No significant difference was observed between the day 3, day 7 and the normal groups.

**Effect of LOS on Muscle Regeneration after Contusion Injury:** The number of centronucleated regenerating myofibers, present in the contusion-injured muscle were counted and compared

**Figure 2**



among the groups, 4 weeks after contusion injury (Figure 2A-E). We observed a significant increase in the number of centronucleated regenerating myofibers in the day 3 and day 7 groups ( $149.0 \pm 25.4$ ,  $123.3 \pm 28.3/\text{hpf}$ ) compared with the other groups (control group;  $91.32 \pm 23.0/\text{hpf}$  and day 0 group;  $94.47 \pm 26.6/\text{hpf}$ ,  $p < 0.05$  respectively, Figure 2E).

**Effect of LOS on Muscle Fibrosis after Contusion Injury:** The areas of fibrotic scar tissue in the contusion injured muscle were calculated and compared among the groups, 4 weeks after contusion injury (Figure 3A-E). The day 3 and day 7 groups showed significantly less fibrosis ( $1.87 \pm 1.0\%$  and  $4.17 \pm 3.1\%$ , respectively) than the control and day 0 groups ( $12.8 \pm 5.0\%$ ,  $12.4 \pm 4.6\%$ ,  $p < 0.05$  respectively, Figure 3E).

**Figure 3**

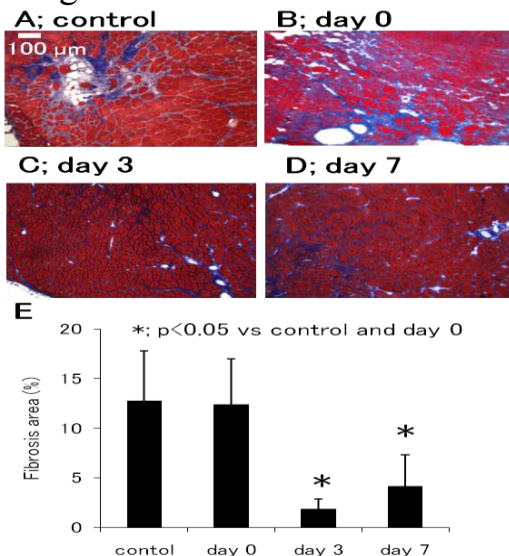
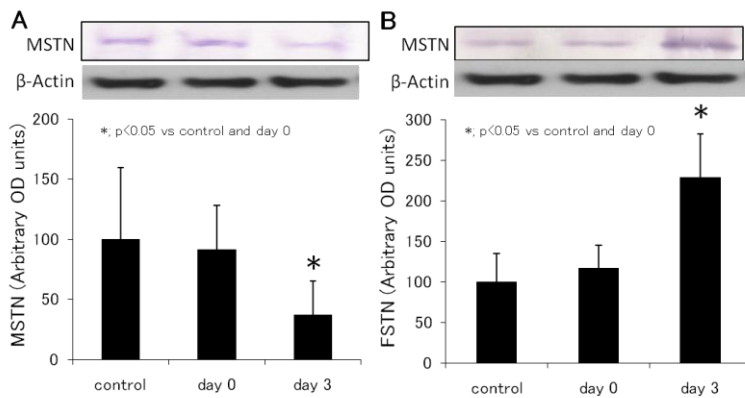


Figure 4



LOS effect on Follistatin and Myostatin expression: The expression of MSTN in the day 3 group (-63% vs control) was significantly lower than in the control and day 0 (-9% vs control, 1 week after injury) groups 1 week after injury ( $p<0.05$ , Figure 4A). Expression of FSTN in the day 3 group (+119% vs control) was significantly greater than in the control and day 0 groups (+17% vs control, 1 week after injury) 1 week after injury ( $p<0.05$ , Figure 4B).

Our previous results showed that we could obtain improvement of muscle healing when administering LOS immediately following injury;

however, the dose of LOS used to obtain these results was 3 times the dose recommended for use in human patients suffering from hypertension. The current study demonstrated that the timing of LOS administration (3 days post-injury) is critical for obtaining optimal results using a lower and safer dose of LOS. In comparison with the other groups, we also observed an increase in the number of centronucleated myofibers, a decrease in the area of fibrosis, and an enhancement in muscle strength when LOS administration was initiated 3 days after muscle injury.

Administration of LOS 3 days after contusion injury, using a human dose equivalent for the treatment of hypertension (10 mg/kg/day), effectively leads to a reduction in MSTN expression, 1 week after injury. We also observed an increase in the number of centronucleated myofibers, a decrease in fibrosis, and an enhancement in muscle strength when LOS was administered 3 days after muscle injury. Wang et al. have demonstrated that LOS significantly blocked the increase of the MSTN protein by blocking angiotensin II, and indicated that angiotensin II increases MSTN expression through the AT1 receptor (5). These results may suggest that LOS administered 3 days after injury can diminish angiotensin II-induced MSTN deposition of type I collagen which is mediated by the AT1 signaling pathway which would then allow for accelerated muscle regeneration.

In addition, the expression of FSTN was observed to be up-regulated in the day 3 group until 2 weeks after injury. It is well known that FSTN, a secreted protein, is able to bind and neutralize the actions of many members of the TGF- $\beta$  superfamily of proteins. In skeletal muscle, FSTN stimulates satellite cell proliferation and FSTN gene therapy has shown promise as a MSTN inhibitor to treat dystrophic mdx muscles (a mouse model of Duchenne muscular dystrophy) by increasing muscle size and strength and reducing fibrosis. Our results support these latter findings since the injured muscle treated with LOS shows an increase in FSTN expression and a decrease in MSTN expression, a finding that correlates with muscle regeneration and fibrosis formation. However, it remains unclear if LOS treatment acts directly on MSTN or through the up-regulation of FSTN.

This study demonstrated that LOS used at the dosage used to treat hypertension in humans is mediated directly through the inhibition of MSTN and/or the up-regulation of FSTN. This study strongly suggests that the use of LOS to expedite the muscle healing process could also be applied to other types of acute muscle injuries and may also be useful for the treatment of degenerative fibrotic muscle disorders. (**Appendix 18**)

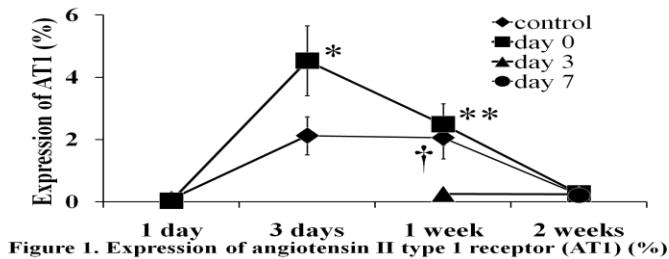
#### b) Signal Pathway for Skeletal Muscle Healing Role of Angiotensin II Receptor Blocker in Mouse

In this study, we investigated the effect of LOS for angiotensin II type 1 receptor (AT1), which was block by LOS regulated myostatin (MSTN) [1] which was a primary negative regulator of the growth and was also a strong stimulator of fibrosis formation, and regeneration of muscle analyzed the expression of MSTN and MyoD, was a regulator of the muscle regeneration [6] of use at different timing after injury.

**Animal model:** The muscle contusion model was developed in tibialis anterior (TA) muscle of C57BL/6J wild-type mice. Concentrations of LOS (125mg) in 1 liter of tap water were administered beginning differently after 0, 3 and 7 days after injury until endpoint (day 0, day 3 and day 7 groups, respectively) while the control group drink tap water (6 mice in each group). These doses were calculated based on the average fluid intake of mice as 10mg/kg/day respectively [6]. One and 3 days, 1 and 2 weeks after injury, we harvested the mouse TA.

**Evaluation of AT1, MSTN and MyoD Expression After LOS Therapy:** The TA muscles were harvested 1 and 3 days, 1 and 2 weeks after injury and were cryosectioned and immunohistochemically stained using antibodies

against AT1 and MSTN were performed to measure the AT1 and MSTN expression in the injured muscles. The TA muscles were harvested 1 and 2 weeks after injury and were cryosectioned and immunohistochemically stained using antibodies against MyoD was performed to measure the MyoD expression in the injured muscles. The expression of AT1, MSTN and MyoD positive areas were calculated using Northern Eclipse software (Empix Imaging Inc).



**Figure 1. Expression of angiotensin II type 1 receptor (AT1) (%)**

\*:  $p < 0.05$  day 0 at 3 days vs control at 3 days and day 0 at 1 day, 1 and 2 weeks

\*\* :  $p < 0.05$  day 0 at 1 week vs day 3 at 1 week and day 0 at 1 day and 2 weeks

†:  $p < 0.05$  control at 1 week vs day 3 at 1 week and control at 1 day, 1 and 2 weeks

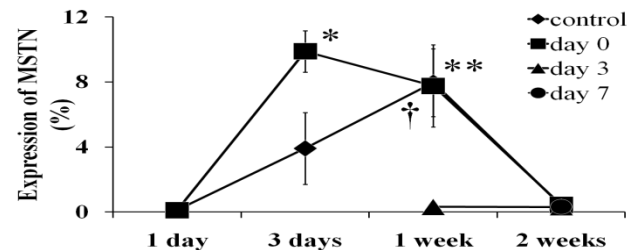
assessed by the ANOVA and Scheffe's F test as post hoc test. Statistical significance was defined as  $p < 0.05$ .

#### *LOS enhanced expression of AT1 (Figure 1):*

We could observe significant increases the expression of AT1 in the day 0 group 3 days after injury when compared with in control at same time. At 1 week after injury, the expression of AT1 in the day 3 group was significant less than in the control and day 0 groups. However, there is no significant difference in each group at 2 weeks after injury.

#### *LOS enhanced expression of MSTN (Figure 2):*

Expression of MSTN was similar result of the expression of AT1. Especially, the expression of MSTN in the day 0 group was significant increases 3 days after injury when compared with in control at same time. At 1 week after injury, the expression of MSTN in the day 3 group was significant less than in the control and day 0 groups. However, there is no significant difference in each group at 2 weeks after injury.



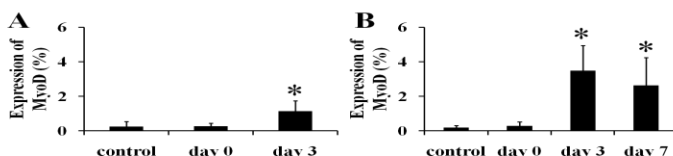
**Figure 2. Expression of myostatin (MSTN) (%)**

\*:  $p < 0.05$  day 0 at 3 days vs control at 3 days and day 0 at 1 day, 1 and 2 weeks

\*\* :  $p < 0.05$  day 0 at 1 week vs day 3 at 1 week and day 0 at 1 day and 2 weeks

†:  $p < 0.05$  control at 1 week vs day 3 at 1 week and control at 1 day, 1 and 2 weeks

**LOS enhanced expression of MyoD (Figure 3):** Expression of MyoD in day 3 was greater than control or LOS treated at day 0 groups 1 week after injury (Figure 3A). Two weeks after injury, the expression of MyoD in the day 3 and day 7 groups were greater than in the control and day 0 groups (Figure 3B).



**Figure 3. Expression of MyoD (%)**

**A: 1 week after injury.** \*:  $p < 0.05$  vs control and day 0

**B: 2 weeks after injury.** \*:  $p < 0.05$  vs control and day 0

and this result indicated the dramatic difference observed in muscle healing between the control group and the day 0 group. We previously reported that the result of muscle force and the number of centronucleated myofibers in the control and day 0 groups are similar at 4 weeks after injury [8], however our current result observed the expression of AT1 and MSTN were increased administrating LOS immediately after injury using

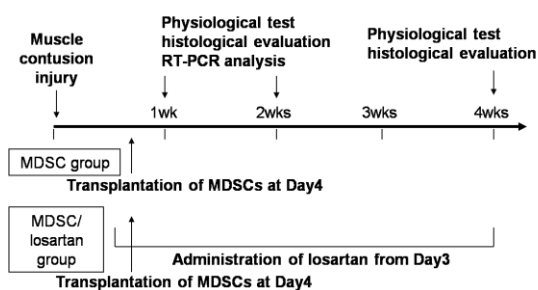
safety dose at 3 days after injury more than control group. It suggests that the increasing AT1 was caused by LOS administrated immediately after injury in inflammation period. Additionally we suggest that the reason of improving muscle force and increasing the number of centronucleated myofibers in day 3 and day 7 groups compared with control and day 0 groups at 4 weeks after injury [9], also LOS administrated 3 or 7 days after injury diminished the expression of MSTN via AT1 receptor more than the effect of LOS administrated immediately after injury, indicated that the expression of MSTN was diminished administrating LOS after inflammation period. Therefore, decreasing the expression of MSTN in day 3 and day 7 groups observed increasing the expression of MyoD at 1 and/or 2 weeks after injury, these effects also probably resulted from increasing in muscle regeneration. Actually, we found that the mechanism of LOS when administered 3 days after muscle contusion injury caused to heal muscle even in safety dose for human. (**Appendix 19**)

### c) Administration of Angiotensin II Receptor Blocker Stimulates Smad7 expression in Muscle Derived Stem Cells Transplanted in Contusion Injured Skeletal Muscle

Muscle contusions are one of the most common muscle injuries in sports medicine. Although these injuries are capable of healing, incomplete functional recovery often occurs. We have previously reported that losartan, one of the FDA approved Angiotensin II Receptor Blockers (ARBs), has been promoted muscle healing and shown to also be anti-fibrotic effect in injured skeletal muscle [2]. On the other hand, rapid revascularization after muscle injury is important for early muscle healing [10]. We have, also, previously shown that muscle derived stem cells (MDSCs) are derived from blood vessels' cells and have a multilineage differentiation potential that includes myogenic and endothelial lineages [11]. In the last ORS meeting, we reported that the better functional recovery after MDSC transplantation could be caused via increase in angiogenesis and decrease in fibrosis. However, our protocol of the MDSCs' transplantation could not completely inhibit the fibrosis formation within the injured muscle. The aims of this study were 1) to find the effect of administration of losartan before MDSCs' transplantation and 2) to investigate the healing mechanism of MDSCs' transplantation with losartan.

The contusion was performed on tibialis anterior (TA) muscle of C57BL/6 wild-type mice [12]. MDSCs were isolated from 3-week-old wild-type mice (C57BL/6J) using a preplate technique as previously described [13].

Figure 1.

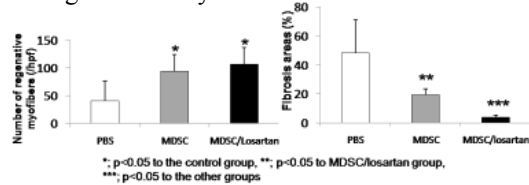


At 4 days post-injury,  $3 \times 10^5$  MDSCs were transplanted directly into the injured TA muscle region ( $n = 15$  mice for each group). Concentrations of LOS (125mg) in 1 liter of drinking water were administered beginning after 3 days post-injury until endpoint. These doses were calculated based on the average fluid intake of mice as 10mg/kg/day. Mice were divided into 3 groups, 1) MDSC/losartan group, 2) MDSC group, and 3) injured control group with PBS injection and drink normal water. At 1, 2, and 4 weeks post injury, a modified in situ force physiological testing was performed [14]. After the testing, animals were sacrificed and the TA muscles were harvested for histological evaluations. Statistical analysis was performed with ANOVA and Scheffe's F test as post hoc test. Statistical significance was defined as  $p < 0.05$ . Refer to Figure 1 for a schematic timeline of the experimental design.

***MDSCs' Transplantation Enhanced Muscle Regeneration in Injured Muscle:*** After hematoxylin and eosin staining, the centronucleated regenerating myofibers in the injured muscle were counted and compared among the groups at 2 weeks post-injury. The MDSC treated groups (MDSC and MDSC/losartan groups) showed a significant higher number of regenerative myofibers (MDSC group,  $131.8 \pm 32.1$ ; MDSC/losartan group,  $132.4 \pm 28.5$ /hpf) when compared with control group ( $40.7 \pm 36.2$ /hpf) (Fig. 2A).

Figure 2.

Investigator: Johnny Huard



MDSC groups ( $48.24 \pm 22.99$  and  $19.39 \pm 4.12\%$ , respectively) (Fig. 2B).

**MDSCs' Transplantation Showed Rapid Improvement of Muscle Strength:** At 2 weeks post-injury, The MDSC treated groups (MDSC and MDSC/losartan groups) showed significant greater specific peak twitch and tetanic forces (twitch;  $44.1 \pm 10.3$  and  $47.2 \pm 13.7$ , tetanic;  $67.2 \pm 16.2$  and  $69.4 \pm 13.1 \text{ g/cm}^2$ , respectively) when compared with control group (twitch;  $24.9 \pm 5.3$ , tetanic;  $46.8 \pm 11.6 \text{ g/cm}^2$ ). Moreover, there was no significant difference between the MDSC treated groups and normal group (twitch;  $36.0 \pm 11.1$ , tetanic;  $64.9 \pm 18.8 \text{ g/cm}^2$ ) (Fig. 3).

At 4 weeks after the injury, The control group showed significant less specific twitch and tetanic forces (twitch;  $13.8 \pm 2.0$ , tetanic;  $17.4 \pm 2.2 \text{ g/cm}^2$ ) when compared with the other groups (MDSC and MDSC/losartan groups) (twitch;  $20.6 \pm 3.1$  and  $22.4 \pm 2.1$ , tetanic;  $25.6 \pm 2.7$  and  $31.9 \pm 2.9 \text{ g/cm}^2$ , respectively). Interestingly, MDSC/losartan group showed a significant greater specific peak tetanic force when compared with MDSC and normal (twitch;  $20.0 \pm 0.8$ , tetanic;  $24.1 \pm 0.8 \text{ g/cm}^2$ ) groups (Fig. 3).

**MDSCs' transplantation after Losartan Treatment Enhanced FSTN and Smad7**

**Expressions in Injured Muscle:** FSTN areas in the injured TA muscles were measured and compared among the groups at 1 week post-injury. MDSC/losartan group ( $0.60 \pm 0.22\%$ ) showed a significant greater FSTN

expression when compared with MDSC and control groups ( $0.29 \pm 0.19$  and  $0.00 \pm 0.00\%$ , respectively) (Fig. 4A). Smad7 areas in the injured TA muscles were measured and compared among the groups at 2 weeks post-injury. MDSC/losartan group showed a significant greater Smad7 ( $28.77 \pm 26.37\%$ ) expressions when compared with control and MDSC groups ( $2.15 \pm 1.86$  and  $8.25 \pm 7.64\%$ , respectively) (Fig. 4B).

The combination therapy of intramuscular transplantation of

MDSCs and administration of losartan following a contusion injury improved overall skeletal muscle healing. Losartan enhanced MDSC differentiation towards myoblasts and inhibited fibrosis formation via increase of Smad7 expression. Furthermore, losartan enhanced the recovery in muscle strength at 4 weeks post-injury. These results suggested a possible mechanism for the beneficial effects of losartan in MDSCs transplanted after skeletal muscle injury, and could contribute to the development of biological treatments to accelerate muscle healing after muscle injury. (Appendix 20)

## Key Research Accomplishment

- Determined that Suramin can stimulate MDSC myogenic differentiation *in vitro*.
- Determined that Suramin can enhance skeletal muscle regeneration and reduce fibrous scar formation following a contusion injury.
- Determined that Suramin's beneficial effects on muscle healing is related to it's ability to enhance the proliferation and differentiation of myoblasts and MDSC and it's ability to inhibit myostatin and up-regulate follistatin.

Figure 3.

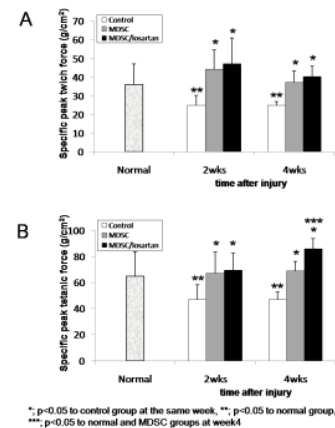
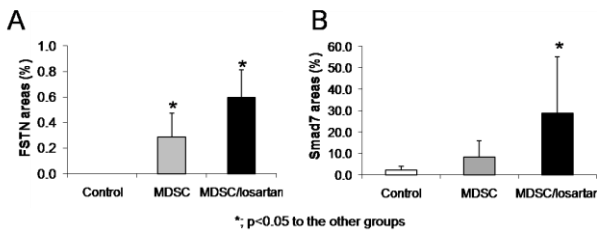


Figure 4.



- Determined that the antifibrotic ability of decorin not only relates to its ability to inhibit TGF- $\beta$ 1 but also myostatin. We further showed that the up or down regulation of TGF- $\beta$ 1 simultaneously had the same effect on myostatin and vice versa.
- Myostatin has been shown to be a negative regulator of skeletal muscle regeneration and a positive regulator of fibrosis deposition which can be down-regulated with decorin and suramin
- Follistatin is intricately involved with the muscle healing process and has been shown to be a positive regulator of muscle regeneration and a negative regulator of fibrosis deposition and can be up-regulated with decorin and suramin.
- Losartan has been shown to block TGF- $\beta$ 1 and have a statistically significant effect on the healing of injured skeletal muscle.
- Losartan is a safe and effective, clinically applicable angiotensin II receptor blocker and has been shown to be a potential safe and effective treatment for aiding in the healing of skeletal muscle injury.
- 1<sup>st</sup> case report of treating a recurrent hamstring injury in a 21 year old man with Losartan is being prepared.
- The continuous administration of Losartan at markedly high dose of 30 mg/kg/day, immediately after skeletal muscle injury, can accelerate skeletal muscle functional recovery.
- 10 mg/kg/day (human safety dose) of LOS treatment initiated at 3 days after contusion injury can enhance structural and functional healing in mouse skeletal muscle.
- The off-label use of Losartan to treat two healthy collegiate athletes with grade 2 biceps femoris injuries. tolerated the course of losartan well with no hypotension or any other side effects. The patients demonstrated recovery of normal flexibility and strength compared to the contra-lateral leg and were ready for return to sports in 9 to 11 weeks after injury.

#### **New Key Accomplishments:**

- The Effect of Timing of Administration of Losartan on Skeletal Muscle Healing After Traumatic Injury
- Signal Pathway for Skeletal Muscle Healing Role of Angiotensin II Receptor Blocker in Mouse
- Administration of Angiotensin II Receptor Blocker Stimulates Smad7 expression in Muscle Derived Stem Cells Transplanted in Contusion Injured Skeletal Muscle

#### **Reportable Outcomes**

- 1) **Nozaki M, Li Y, Zhu J, Ambrosio F, Fu FH and Huard J.** The use of suramin to improve skeletal muscle healing after contusion injury. Presented as a poster at the Orthopaedic Research Society meeting, Feb. 2007.
- 2) **Li Y, Li J, Zhu J, Sun B, Branca M, Tang Y, Foster W, Xiao X, Huard J.** Decorin gene transfer promotes muscle cell differentiation and muscle regeneration. Mol Ther 2007 Sep; 15(9):1616-1622.



- 3) **Zhu J, Li Y, Shen W, Qiao C, Ambrosio F, Lavasani M, Nozaki M, Branca M, Huard J.** Relationships between TGF- $\beta$ 1, myostatin, and decorin: Implications for skeletal muscle fibrosis. *J Biol Chem* 2007 Aug; 282(35):25852-63.
- 4) **Zhu J, Li Y, Huard J.** Decorin Interacts with Myostatin Activity-Implications for Skeletal Muscle Healing. The Orthopaedic Research Society (ORS) 53rd Annual Meeting; Feb 12-14, 2007; San Diego, CA
- 5) **Shen W, Huard J. Tissue therapy: Implications of regenerative medicine for skeletal muscle.** Attala A, Lanza R, Thomson J, Nerem RM, editors. *Principles of Regenerative Medicine*. Elsevier Academic Press, 2007; 1232--1247, **chapter 72**. (Invited Book Chapter)
- 6) **Zhu J, Li Y, Branca M, Huard J.** Follistatin improves skeletal muscle healing after injury. The Orthopaedic Research Society (ORS) 53rd Annual Meeting; Feb 12-14, 2007; San Diego, CA
- 7) **Matsuura T, Li Y, Giacobino JP, Fu F, Huard J.** Skeletal muscle fiber type conversion during the repair of mouse soleus: Potential implications for muscle healing after injury. *J. Orthop Res* 2007 Nov; 25(11): 1534-1540. Figure featured on front cover as cover art.
- 8) **Nozaki M, Li Y, Zhu J, Uehara K, Ambrosio F, Fu F, Huard J.** Suramin can enhance the skeletal muscle healing by blocking myostation. The Orthopaedic Research Society (ORS) 54<sup>th</sup> Annual Meeting; March 2-5, 2008; San Francisco, CA.
- 9) **Nozaki M, Li Y, Zhu J, Ambrosio F, Uehara K, Fu F, Huard J.** Improved muscle healing after contusion injury by the inhibitory effect of Suramin on Myostatin, a negative regulator of muscle growth. *Am J Sports Med*, 2008 Dec; 36(12):2354-62.
- 10) **Bedair H, Karthikeyan T, Quintero AJ, Li Y, Huard J.** Angiotensin II Receptor Blockade administered after injury improves muscle regeneration and decreases fibrosis in normal skeletal muscle. *Am J Sports Med*, 2008 Aug; (36)8: 1548-1555.
- 11) **Shen W, Li Y, Zhu J, Schwendener R, Huard J.** Interaction between macrophages, TGF-beta 1, and the COX-2 pathway during the inflammatory phase of skeletal healing after injury. *J of Cellular Physiology* 2008 Feb; 214(2): 405-412.
- 12) **Ambrosio, F, Li Y, Usas A, Boninger, ML, Huard J.** Muscle repair after injury and disease. *Orthopaedic Biology and Medicine, Musculoskeletal Tissue Regeneration: Biological Materials and Methods*. The Humana Press Inc, 2008. (Invited Review)
- 13) **Zhu J, Ma J, Lu A, Qiao C, Li J, Li Y, Xiao X, Huard J.** Blocking Myostatin Improves the Success of Muscle Cell Transplantation. AFIRM All Hands Meeting; January 13- 16, 2009; St. Pete, FL.
- 14) **Uehara K, Nozaki M, Zhu J, Quintero A, Ota S, Fu F, Huard J.** Angiotensin II Receptor Blocker Ameliorates Skeletal Muscle Healing in a Dose Dependent Manner. 55<sup>th</sup> Annual Orthopaedic Research Society Meeting; Las Vegas, Nevada; February 22-25, 2009.
- 15) **Zhu J, Ma J, Qiao C, Jianbin L, Yong L, Xiao X, Huard J.** Blocking Myostatin Improves Muscle Healing Via Enhancement of Angiogenesis. 55<sup>th</sup> Annual Orthopaedic Research Society Meeting; Las Vegas, Nevada; February 22-25, 2009.

- 16) Yuri Chun, MD, James Irrgang, PhD, Tanya Hagen, MD, Vonda Wright, MD, Freddie Fu, MD, Johnny Huard, PhD.** Improving Recovery after a Recurrent Hamstring Injury with an Angiotensin II Receptor Blocker Therapy: a Case Report and a Review of Literature (**Under revision adding 2<sup>nd</sup> patient, refer to Appendix 17** )
- 17) Uehara, K; Kobayashi, T; Ota, S; Bin, S; Tobita, K; Ambrosio, F; Fu, FH; Huard, J.** Angiotensin Receptor Blocker Improves Skeletal Muscle Function Recovery in a Dose Dependent Manner. 56<sup>th</sup> Annual Orthopaedic Research Society Meeting; New Orleans, LA; March 6-9, 2010.
- 18) Kobayashi, T; Uehara, K; Ota, S; Bin, S; Tobita, K; Ambrosio, F; Fu, FH; Huard, J.** Angiotensin II Receptor Blocker Ameliorates Skeletal Muscle Healing, 56<sup>th</sup> Annual Orthopaedic Research Society Meeting; New Orleans, LA; March 6-9, 2010.
- 19) Yuri Chun MD, Sheila J M Ingham MD, James Irrgang PhD, Tanya Hagen MD, Freddie Fu MD, Burhan Gharaibeh, Vonda Wright MD, Johnny Huard, PhD.** Improving Recovery Following Recurrent Hamstring Injury Using an Angiotensin II Receptor Blocker: Two Case Studies; 56<sup>th</sup> Annual Orthopaedic Research Society Meeting; New Orleans, LA; March 6-9, 2010.
- 20) Tetsuo Kobayashi, Kenji Uehara, Shusuke Ota, Kimimasa Tobita, Fabrisia Ambrosio, James H. Cummins, Freddie H. Fu and Johnny Huard.** The Effect of Timing of Administration of Losartan on Skeletal Muscle Healing After Traumatic Injury. 57<sup>th</sup> Annual Orthopaedic Research Society Meeting; Long Beach; January 2011.
- 21) Kobayashi, T; Uehara, K; Ota, S; Terada, S; Cummins, JH; Fu, FH; Huard, J** Signal Pathway for Skeletal Muscle Healing Role of Angiotensin II Receptor Blocker in Mouse. 57<sup>th</sup> Annual Orthopaedic Research Society Meeting; Long Beach; January 2011.
- 22) Terada, S; Kobayashi, T; Ota, S; Gharaibeh, B; Fu, FH; Huard, J** Administration of Angiotensin II Receptor Blocker Stimulates Smad7 expression in Muscle Derived Stem Cells Transplanted in Contusion Injured Skeletal Muscle. 57<sup>th</sup> Annual Orthopaedic Research Society Meeting; Long Beach; January 2011.

## Conclusions

This line of work has enabled us to identify three potentially useful compounds that could be utilized to prevent fibrous scar formation and aid in the healing and regeneration of injured skeletal muscle. Suramin is a drug that has been used clinically to treat individuals infected with trypanosomes and worms and is currently being investigated for the treatment of prostate cancer; therefore it could potentially be applied clinically expeditiously. Decorin too has shown great promise; however, it is not currently FDA approved for clinical application and would require more time to apply clinically since it would need to undergo clinical trials. From a basic science standpoint these studies have demonstrated the mechanisms that these two drugs utilize for their beneficial effect on the healing and regeneration of skeletal muscle. They firstly act by inhibiting two components that are major initiators of the fibrosis cascade, TGF-B1 and myostatin. They have also been shown to facilitate regeneration and healing by promoting myoblast and MDSC proliferation and differentiation into myotubes in vitro and myofibers in vivo. One of the pathways that they seem to work on for this enhancement in regeneration appears to be the up- regulation of follistatin. Additional work is currently underway to determine the pharmacokinetics of these two promising compounds. Finally we have been exploring the use of the angiotensin II receptor blocker, Losartin, and have reported the 1<sup>st</sup> case study that demonstrates this well tolerated drug for the treatment of a patient suffering from recurrent hamstring injury. Additional animal



studies are underway to explore the molecular mechanisms involved with the successful use of this drug to treat skeletal muscle injuries besides it's ability to block TGF-B1.

## Appendices

**Appendix 1: Nozaki M, Li Y, Zhu J, Ambrosio F, Fu FH and Huard J.** The use of suramin to improve skeletal muscle healing after contusion injury. Presented as a poster at the Orthopaedic Research Society meeting, Feb. 2007.

**Appendix 2: Li Y, Li J, Zhu J, Sun B, Branca M, Tang Y, Foster W, Xiao X, Huard J.** Decorin gene transfer promotes muscle cell differentiation and muscle regeneration. *Mol Ther* 2007 Sep; 15(9):1616-1622.

**Appendix 3: Zhu J, Li Y, Shen W, Qiao C, Ambrosio F, Lavasani M, Nozaki M, Branca M, Huard J.** Relationships between TGF- $\beta$ 1, myostatin, and decorin: Implications for skeletal muscle fibrosis. *J Biol Chem* 2007 Aug; 282(35):25852-63.

**Appendix 4: Zhu J, Li Y, Huard J.** Decorin Interacts with Myostatin Activity-Implications for Skeletal Muscle Healing. The Orthopaedic Research Society (ORS) 53rd Annual Meeting; Feb 12-14, 2007; San Diego, CA

**Appendix 5: Zhu J, Li Y, Branca M, Huard J.** Follistatin improves skeletal muscle healing after injury. The Orthopaedic Research Society (ORS) 53rd Annual Meeting; Feb 12-14, 2007; San Diego, CA

**Appendix 6: Nozaki M, Li Y, Zhu J, Uehara K, Ambrosio F, Fu F, Huard J.** Suramin can enhance the skeletal muscle healing by blocking myostation. The Orthopaedic Research Society (ORS) 54<sup>th</sup> Annual Meeting; March 2-5, 2008; San Francisco, CA.

**Appendix 7: Nozaki M, Li Y, Zhu J, Ambrosio F, Uehara K, Fu F, Huard J.** Improved muscle healing after contusion injury by the inhibitory effect of Suramin on Myostatin, a negative regulator of muscle growth. *Am J Sports Med*, 2008 Dec; 36(12):2354-62.

**Appendix 8: Bedair H, Karthikeyan T, Quintero AJ, Li Y, Huard J.** Angiotensin II Receptor Blockade administered after injury improves muscle regeneration and decreases fibrosis in normal skeletal muscle. *Am J Sports Med*, 2008 Aug; (36)8: 1548-1555.

**Appendix 9: Shen W, Li Y, Zhu J, Schwendener R, Huard J.** Interaction between macrophages, TGF-beta 1, and the COX-2 pathway during the inflammatory phase of skeletal healing after injury. *J of Cellular Physiology* 2008 Feb; 214(2): 405-412.

**Appendix 10: Zhu J, Ma J, Lu A, Qiao C, Li J, Li Y, Xiao X, Huard J.** Blocking Myostatin by AAV2-Delivered Myostatin Propeptide Improves Muscle Cell Transplantation . Orthopaedic Research Society; Las Vegas, Nevada; February 22-25, 2009.

**Appendix 11: Uehara K, Nozaki M, Zhu J, Quintero A, Ota S, Fu F, Huard J.** Angiotensin II Receptor Blocker Ameliorates Skeletal Muscle Healing in a Dose Dependent Manner. Orthopaedic Research Society; Las Vegas, Nevada; February 22-25, 2009.

**Appendix 12: Zhu J, Ma J, Qiao C, Jianbin L, Yong L, Xiao X, Huard J.** Blocking Myostatin Improves Muscle Healing Via Enhancement of Angiogenesis. Orthopaedic Research Society; Las Vegas, Nevada; February 22-25, 2009.

**Appendix 13: Uehara, K; Kobayashi, T; Ota, S; Bin, S; Tobita, K; Ambrosio, F; Fu, FH; Huard, J.** Angiotensin Receptor Blocker Improves Skeletal Muscle Function Recovery in a Dose Dependent Manner. 56<sup>th</sup> Annual Orthopaedic Research Society Meeting; New Orleans, LA; March 6-9, 2010.

**Appendix 14: Kobayashi, T; Uehara, K; Ota, S; Bin, S; Tobita, K; Ambrosio, F; Fu, FH; Huard, J.** Angiotensin II Receptor Blocker Ameliorates Skeletal Muscle Healing, 56<sup>th</sup> Annual Orthopaedic Research Society Meeting; New Orleans, LA; March 6-9, 2010.

**Appendix 15: Yuri Chun MD, Sheila J M Ingham MD, James Irrgang PhD, Tanya Hagen MD, Freddie Fu MD, Burhan Gharaibeh, Vonda Wright MD, Johnny Huard, PhD.** Improving Recovery Following Recurrent Hamstring Injury Using an Angiotensin II Receptor Blocker: Two Case Studies; 56<sup>th</sup> Annual Orthopaedic Research Society Meeting; New Orleans, LA; March 6-9, 2010.

**Appendix 16: Jinhong Zhu, M.D., Ph.D., Yong Li, M.D., Ph.D, Aiping Lu, MD, Burhan Gharaibeh Ph.D., Jianqun Ma, M.D., Ph.D., Tetsuo Kobayashi, M.D., Ph.D., Andres J. Quintero, M.D., Johnny Huard, Ph.D.** Follistatin Improves Skeletal Muscle Healing After Injury & Disease Through an Interaction with Muscle Regeneration, Angiogenesis and Fibrosis . (Under revision for Am J. Pathology)

**Appendix 17: Kenji Uehara, Yuri Chun, Shusuke Ota, Tetsuo Kobayashi, Sheila Ingham, Masahiro Nozaki, Kimimasa Tobita, James Irrgang, Freddie Fu, Vonda Wright, Tanya Hagen, and Johnny Huard.** Improving Recovery Following Muscle Injury Using an Angiotensin II Receptor Blocker in Both an Animal Model and in Human Patients: From the Bench to the Bedside (In preparation)

#### **New Appendices:**

**Appendix 18: Tetsuo Kobayashi, Kenji Uehara, Shusuke Ota, Kimimasa Tobita, Fabrisia Ambrosio, James H. Cummins, Freddie H. Fu and Johnny Huard.** The Effect of Timing of Administration of Losartan on Skeletal Muscle Healing After Traumatic Injury. 57<sup>th</sup> Annual Orthopaedic Research Society Meeting; Long Beach; January 2011.

**Appendix 19 Tetsuo Kobayashi, MD. PhD; Kenji Uehara, MD. PhD; Shusuke Ota, MD. PhD; Satoshi Terada, MD; James H. Cummins; Freddie H. Fu, MD, DSc (Hon), DPs (Hon); Johnny Huard, PhD** Characterization of Losartan's Mechanism of Action for Muscle Healing. 57<sup>th</sup> Annual Orthopaedic Research Society Meeting; Long Beach; January 2011.

**Appendix 20 \*Terada, S; \*Kobayashi, T; \*Ota, S; \*Gharaibeh, B; \*\*Fu, FH; \*Huard, J** Administration of Angiotensin II Receptor Blocker Stimulates Smad7 expression in Muscle Derived Stem Cells Transplanted in Contusion Injured Skeletal Muscle. 57<sup>th</sup> Annual Orthopaedic Research Society Meeting; Long Beach; January 2011.

#### **References:**

1. Li Y, *et al.*, Am J Pathol 161: 895-907, 2002.
2. Bedair HS, *et al.*, Am J Sports Med 36: 1548-1554, 2008.
3. Lee SJ, *et al.*, Proc Natl Acad Sci U S A 98: 9306-9311, 2001.
4. Sasaki M, *et al.*, Life Sci 75: 869-880, 2004.

5. Wang BW, *et al.*, J Endocrinol 197: 85-93, 2008.
6. Kobayashi, *et al.*, 56th *ORS meeting*, 2010.
7. Tharaux PL, *et al.*, *Hypertension*. 2000; 36: 330-336.
8. Karalaki M, *et al.*, *In Vivo*. 2009; 23: 779-796.
9. Uehara K, *et al.*, *AJSM* in submitting.
10. Arsic N, *et al.*, Mol Ther. 2004 Nov;10(5):844-54
11. Zeng B, *et al.*, Nat Biotechnol. 2007; 25(9):1025-34..
12. Menetrey J, *et al.*, Am J Sports Med. 1999; 27(2):222-229.
13. Gharaibeh B, *et al.* Nat Protoc 2008; 3:1501-9.
14. Dellorusso C, *et al.*, J Muscle Res Cell Motil. 2001; 22(5):467-475.

**Project # 2 Final Report\*\***  
**Improving muscle healing through digestion of scar tissue via MMP-1**  
**(Yong Li)**

**\*\*Note that no additional work has been performed on this project. The final report for this project was written in the 2010 Progress report. The information provided below is simply a reiteration of that report.**

**Introduction:**

Muscle injuries, which occur most frequently during sports activity, military training and battle; present a challenging problem in traumatology. After injury, damaged muscle fibers undergo a natural process of necrosis and the resulting dead tissue is removed by infiltrating lymphocytes. Meanwhile, locally released growth factors stimulate muscle regeneration by activating satellite cells. Unfortunately, the process of muscle regeneration is often incomplete from overgrowth of the extracellular matrix (ECM) leading to significant local fibrosis (i.e., fibrous scar formation). This scar tissue impedes the formation of normal muscle fibers in the injured muscle, resulting in incomplete functional recovery and a propensity for re-injury. We have begun to study the mechanism behind the fibrosis that occurs in injured skeletal muscle. Our previous studies have demonstrated that myogenic cells (including muscle-derived stem cells [MDSCs]) and regenerating myofibers in lacerated muscle can differentiate into fibrotic cells, and that transforming growth factor (TGF)- $\beta$ 1 is a major stimulator of this differentiation. Using different animal models of muscle injury, we have investigated biological approaches by which to prevent fibrosis and thereby improve muscle healing. However, it often is not possible to treat injured muscles before the initiation of fibrosis—most patients with muscle injuries seek treatment only after the onset of fibrous scar formation, and the concomitant pain and functional deficits it produces. Moreover, chronic diseases (e.g., Duchenne muscular dystrophy [DMD]) generally present significant amounts of fibrous scar tissue within the patients' muscles. Because prevention of fibrosis is infeasible in many cases, the development of a novel therapeutic approach by which to digest existing fibrous scar tissue and improve muscle healing would be very significant.

Matrix metalloproteinase type-1 (MMP1), a naturally occurring collagen-digesting enzyme, has shown great capacity for digesting fibrous scar formations in various tissues. Additionally, MMP1 is also able to increase cell migration in many tissues. We believe that MMP1 is able to facilitate the healing of injured muscle by digesting fibrous scar tissue and improving the local environment in which muscle regeneration occurs. Results obtained from this project may lead to the development of gene therapy applications that eliminate scar tissue within skeletal muscle. Such applications could drastically improve the regeneration of muscles damaged by trauma or by chronic muscle diseases, such as Duchenne and Becker muscular dystrophies.

In the past two years, we have completed most of the proposed experiments. Through our work on **Objective #1**, we have determined that MMP1 increased muscle cell migration and differentiation/fusion capacity *in vitro*. *In vivo*, we also determined that MMP1 could improve muscle healing through increasing muscle cell migration, differentiation and regeneration (**Objective #2**). Finally, we have discovered that MMP1 gene transfer enhanced muscle cell migration and differentiation *in vitro* and *in vivo* (**Objective #3**).

**Body:**

**Technical Objective #1: To assess the effect of MMP1 on muscle cells *in vitro*.**

This proposed experiment has been completed in the past two years. Results from this objective indicate that MMP1 is able to inhibit fibroblast growth and collagen deposition as well as enhance myoblasts migration and fusion/differentiation of these cells *in vitro*. The completed experiment has carried out two publications in the *Journal of Applied Physiology* [2007;102(6):2338-2345] and *American Journal of Pathology* [2009;174(2):541-549].

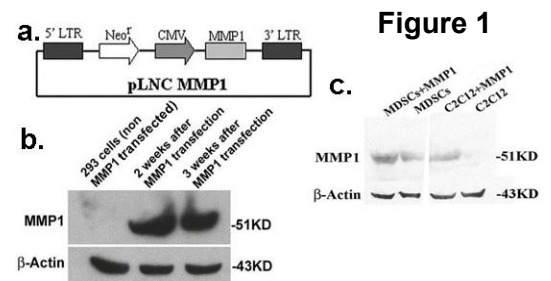
**Technical Objective #2: To assess the effects of MMP1 on skeletal muscle *in vivo*.**

In this objective we observed the effects of MMP1 on skeletal muscle healing in animal models (*in vivo*). We have finished most of this proposed experiment. By using a reproducible muscle injury model in mice that induced significant fibrous scar formation, hindered myofiber regeneration and slowed muscle healing, we have determined that MMP1 can digest the existing fibrous scar and promote muscle healing in the injured skeletal muscles. This proposed experiment has been completed in the past year, and this study has been published by the *Journal of Applied Physiology* 2007;102(6):2338-2345 (Please see attached copy of manuscript). In addition, to observe the effect of MMP1 on muscle cell migration and differentiation *in vivo*, we have selected MDX mice, a mouse model for Duchenne muscular dystrophy [DMD], to investigate if MMP1 could enhance muscle cell migration and differentiation *in vivo*. Our results have substantiated this point and showed that MMP1 could enhance muscle cell fusion as well as migration in dystrophic muscle. This research have been published by *American Journal of Pathology* (2009;174(2);541-549). (Please see attached copy of manuscript).

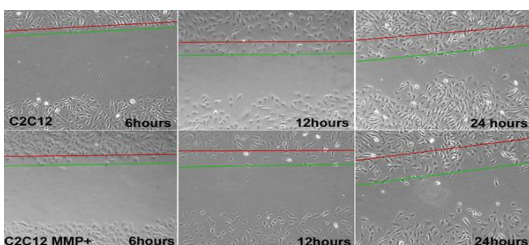
**Technical Objective #3: To assess the use of MMP1-based gene therapy to digest fibrous scar tissue within injured skeletal muscle.**

The primary aim of this proposal is to investigate whether MMP1 gene transduction in implantable myoblasts can extend MMP1 function as a means of digesting fibrous scar tissue and promoting muscle cell migration, fusion and regeneration within injured skeletal muscle. MMP1 can degrade collagens, but undergoes self-degradation, which results in a short biological half-life. As a result, the fibrous scar tissue has the potential to reform following MMP1 degradation. To extend the function of MMP1, we have constructed a retrovirus vector encoding the MMP1 gene. The updated results as following:

**1. MMP1 plasmid constructs:** To extend the function of MMP1, we have constructed a retrovirus vector encoding the MMP1 gene. The Bgl II (blunt ended)/Sal I fragment of pCllase I (ATCC, Rockville, MD), including all coding regions of the human MMP1 gene, was cloned into the Not I (blunt ended)/Xho I site of pLNCX2 (Retroviral Vector, CLONETECH) to generate pLNC MMP1 (**Fig. 1a**). Phoenix 293 cells were transfected (ATCC, Rockville, MD) with pLNC MMP1 using the liposome technique (DOTAP, Boehringer Mannheim), and G418 medium was used to select for the transfected cells. Western blot analysis was used to verify the selected clone cells' expression of MMP1 (**Fig. 1b**). The supernatant from the culture containing the cloned 293 cells was collected to evaluate the titer and transfer to myoblasts (C2C12) and MDSCs. Both transferred C2C12 and MDSC cultures expressed high levels of MMP1 (**Fig. 1c**).



**2. MMP-1 gene transduction stimulated myoblasts to increase migration.** MMP1 gene transferred C2C12 cells and control C2C12 cells were cultured in medium containing Dulbecco's Modified Eagle's Medium (DMEM, Invitrogen, Carlsbad, CA), 10% fetal bovine serum, 10% horse serum, 0.5% chicken embryo extract, and 1% penicillin/streptomycin (P/S) at 37°C in a 5% CO<sub>2</sub> atmosphere in 12 well plates. Cells were then placed in serum-free DMEM supplemented with 1% P/S alone. An artificial wound was created by disrupting the monolayer with a sterile plastic pipette tip. Cells were incubated for 6, 12 and 24 hours to allow for migration back into the wound area. Cells were then fixed in cold methanol, washed with PBS, and then stained with DAPI to help visualize migration distance. We observed that MMP-1 gene transduction (**bottom row, Fig. 2**) promoted C2C12 cell migration

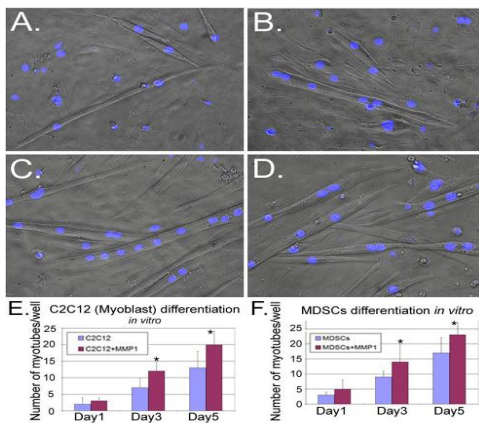
**Figure 2**

into an artificially created wound faster than control C2C12 (*top row, Fig. 2*).

**3. Gene transfer of MMP1 enhances myoblast differentiation *in vitro*.** We investigated whether MMP1 gene transduction has any effect on myogenic cell differentiation. MMP1 cloned myoblasts (C2C12), MDSCs and their control non-gene-transferred cells were separately plated into 12-well-plates and cultured with differentiation medium (2% H.S.) for up to 5 days. Results indicate that the MMP1 gene-transferred myogenic cells resulted in increased numbers of fused myotubes compared to control cells (**Fig. 3**). Myoblasts (C2C12) (**Fig. 3A**) and MDSCs (**Fig. 3B**) fused into myotubes in differentiation medium at their usual levels, however, both MMP1 gene-transferred myoblasts (**Fig. 3C, E**) and MDSCs (**Fig. 3D, F**) increased their differentiation capacity (\* $P < 0.05$ ). It is unclear what mechanism underlies MMP1's up-regulation of the differentiation of

myogenic cells, however, MMP1 down-regulation of fibronectin could be one of the culprits 9. It is also possible that MMP1 can directly affect myogenic cell fusion 10. Our further studies will investigate the relationship between MMP1 expression, the level of fibronectin secretion and myogenic cell differentiation, as well as the underlying mechanisms involved.

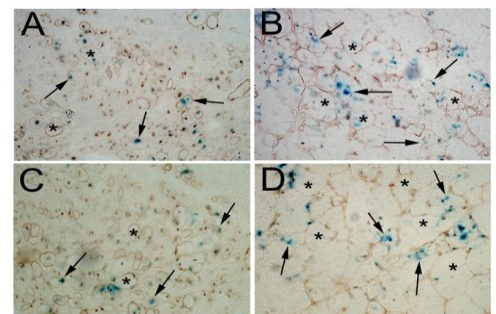
**Figure 3**



performed after cell transplantation, whereupon we detected both LacZ-positive (blue; see arrows in **Fig. 4A-D**) and dystrophin-positive (brown; see asterisks; **Fig. 4A-D**) myofibers in the host muscle at 2 weeks (**Fig. 4A, B**) and 4 weeks (**Fig. 4C, D**) after cell transplantation. However, we discovered that the MMP1-expressing C2C12 fuse/differentiate into better muscle grafts (**Fig. 4B, D**) after transplantation into the skeletal muscle of MDX mice than the control C2C12-transplanted groups (**Fig. 4A, C**) at both 2 and 4 weeks after cell transplantation. In future studies, we will measure the number and the diameter of LacZ-positive and dystrophin-positive myofibers from the skeletal muscle of control and MMP1-expressing cell therapy groups.

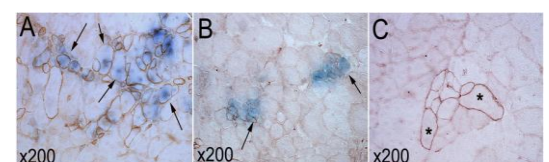
**4. MMP1 gene therapy improves myoblast transplantation.** To investigate whether these MMP1-expressing cells are able to produce a better muscle graft in the skeletal muscle of MDX/SCID (a dystrophic/immunodeficient mouse model) mice, we used a retrovirus vector to transfer the *LacZ* marker gene into genetically altered C2C12 cells that expressed MMP1 as well as control C2C12 cells that did not express MMP1. These cells were then separately transplanted into the skeletal muscle of MDX/SCID mice. Histological analysis was

**Figure 4**



**5. MMP1 gene transduction increases myoblast migration *in vivo*.** We selected both genetically engineered MMP1 expressing C2C12 (myoblasts) and C2C12 control cells as donor cells. Both cells were marked with the *LacZ* gene as a track marker (see above). Equal quantities of MMP1-gene-transferred C2C12 cells and control C2C12 cells ( $1 \times 10^5$  cells) were separately injected systemically into the tail veins of MDX/SCID mice. At various time-points (1, 2, and 3 weeks) after injection, the mice were sacrificed, and the muscle tissues including skeletal muscles, heart, and diaphragm muscles were harvested for histological analysis. In the MMP1 gene-transfected C2C12 injected mice, we detected some LacZ positive myofibers within the skeletal muscles at 2 weeks after injection (**Fig. 5A**). By immunohistochemistry of ABC staining (ABC kit, Vector Laboratory, Inc., CA), we discovered that the location of the LacZ positive myofibers matched the location of the dystrophin positive myofibers in these muscles (arrows, **Fig. 5A**). However, there were

**Figure 5**

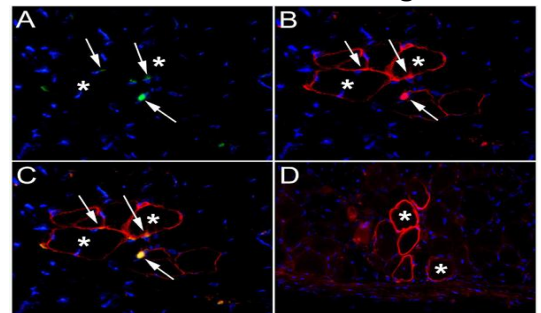




few LacZ and dystrophin positive myofibers detected within the skeletal muscle of the control (non-MMP1 treated) C2C12 injected mice (*arrows, Fig. 5B*); furthermore, some of the dystrophin positive, LacZ negative myofibers (*asterisks, Fig. 5C*) could be reverted myofibers that were located in the skeletal muscle of MDX mice. Results from this pilot study could support the potentially beneficial effect of MMP1 on myogenic cell migration. Western blot analysis has provided evidence that MDSCs alone can express a low level of MMP1 compared to the C2C12 myoblasts (*Fig. 1C*). In fact, our previous study also observed MDSCs displaying better migratory capacity in the *in vivo* animal model 11,12. The migratory ability of MDSCs may be due to the low-level expression of MMP1.

**6. Myoblasts genetically engineered to express MMP1 display a strong migration capacity following systemic delivery into MDX mice.** To investigate whether the systemic delivery of MMP1-expressing myoblasts could migrate into the diaphragm of MDX mice, we have performed immunohistochemistry to examine co-localization staining of the LacZ marker and dystrophin genes in the host diaphragm. Results show that neither LacZ-positive (b-galactosidase) nor dystrophin-positive myofibers were found in the diaphragm muscle following systemic delivery of the control C2C12 into MDX mice. We did, however, discover LacZ-positive myofibers (*green, arrows; Fig. 6A, C*) co-expressed with dystrophin myofibers (*red, asterisks; Fig. 6B, C*) within the diaphragm of MDX mice after systemic injection of C2C12 that were genetically engineered to express MMP1. We also detected some myofibers that expressed dystrophin within the intercostal muscles of the MDX mice that received systemic delivery of our MMP1-expressing C2C12 (*red, asterisks; Fig. 6D*). These results support the notion that MMP1 is able to increase myoblast migration and may help spread donor cells to all types of muscles after systemic delivery.

**Figure 6**



**Future plans:** We have successfully completed **Objective #1 & #2**. For **Objective #3**, we have finished a majority of the proposed experiment. We will focus on preparing manuscripts and one other minor experiment. Based on our results, the new proposal is under discussion with my research team. We expect to investigate the mechanism behind MMP1 in the muscle healing process in the forthcoming project (if funded), by examining how the MMP1 application or MMP1 gene therapy relates to muscle cell precursors, e.g. satellite cells and stem cells populations. More importantly, we have discovered a potential relationship between MMP1 application and angiogenesis or reinnervation, both of which are key aspects of functional recovery in injured skeletal muscle.

#### **Key Research Accomplishments:**

1. Discovery of the effect of MMP1 on muscle cells, resulting in increased migration and differentiation of myogenic cells *in vitro*.
2. Discovery of the effect of MMP1 on scarring skeletal muscle, namely, the digestion of fibrous scar tissue, and improved muscle healing *in vivo*.
3. Discover of the effect of MMP1 on muscle cell migrations and fusion in skeletal muscle of mice *in vivo*.
4. Discovery of MMP1 gene transfer to extend its half-life, which prolongs MMP1 function during its application both *in vitro* and *in vivo*.

#### **Reportable outcomes:**

*Two manuscripts have been published:*

1. Bedair H, Liu TT, Kaar J, Shown B, Russell A, Huard J, Li Y\*, Matrix Metalloproteinase (MMP) Therapy Improves Muscle Healing. *J Applied Physiology* 2007 Jun;102(6):2338-45.
2. Wang W, Pan HY, Murray K, Jefferson M, Li Y. MMP1 promotes muscle cells migration and differentiation. *American J Pathology* 2009, 174 (2); 541-549.

We have prepared another manuscript to summarize our results from **Objective #3** to be entitled, –MMP1 gene therapy to enhance muscle cell migration and differentiation”.

**Six Abstracts** have been presented at five different national and international conferences and have won two awards in past years: The Award for Outstanding Research in Biochemistry/Cell Biology and the prestigious Award for Overall Excellence in Research at the 2006 AMA-MSS National Research Poster Competition.

Besides this funded study, we have been invited to write MMP related **Three Reviews** as following journals:

1. Mu XD, Wang W, Li Y. Myoblast transplantation and fibrosis prevention in diseased muscle (invited review). *US Musculoskeletal Review*, (2009; 4:1)
2. Bellayr I, Li Y. Biochemical insights into the role of matrix metalloproteinases in the regeneration: challenges and recent developments. *Future Medicinal Chemistry (invited review) (2009)*
3. **Chen XP, Li Y. Role of** matrix metalloproteinases in skeletal muscle: migration, differentiation, and regeneration. *Cell Adhesion & Migration* (invited, 2009)

#### **Conclusion:**

*In vitro*, we have seen that MMP1 can enhance muscle cell migration and differentiation. The migration–related proteins are also up–regulated within MMP1–treated muscle cells. *In vivo*, the fibrous scar tissues that form within traumatically injured skeletal muscle could limit transplanted myogenic cell migration, fusion, and regeneration, thus slow the overall muscle healing process. However, muscle healing was greatly improved following MMP1 treatment within these scarred skeletal muscles. We also discovered that the use of MMP1 gene–transferred myoblasts resulted in an increased differentiation capacity *in vitro* and enhanced muscle cell migration *in vivo*.

#### **Appendix and Reference:**

The manuscript entitled –Matrix Metalloproteinase Therapy Improves Muscle Healing” has been published on the *Journal of Applied Physiology* 2007;102(6):2338-2345 resulted from **Objective #2**, The manuscript entitled –MMP1 enhances muscle cell migration and differentiation” has been published on the *American J Pathology* 2009, 174 (2); 541-549 resulted from **Objective #1 & #2**, and Six abstracts which are attached in the **Appendix**. The majority of relevant references may also be found in these manuscripts. Three review articles will be showed public soon.



**Project # 3 Final Report**  
**Repairing injured skeletal muscle through myogenic endothelial cells**  
**(Bruno Peault)**

**INTRODUCTION**

Upon muscle injury, satellite cells, the professional myogenic progenitors present in skeletal muscle, can divide, differentiate and fuse to generate myofibers<sup>1, 2</sup>. Injection of myoblasts has been attempted to repair both skeletal and cardiac muscles in animals and humans<sup>3-5</sup> and was to some extent successful but severe limitations were also encountered after myoblast implantation in both tissues<sup>3, 6, 7</sup>. Muscle regeneration might be improved by transplanting stem cells, in some instances after therapeutic gene transfer, instead of later myogenic progenitors<sup>8-12</sup>.

As described in other sections of this report, we have previously isolated, based on their slow adherence in culture, early myogenic progenitor cells, named muscle derived-stem cells (MDSC), that more efficiently regenerate both skeletal and cardiac muscles than satellite cells<sup>9, 13</sup>. MDSC were isolated retrospectively from cultured skeletal muscle; therefore their origin, identity and anatomic location in the native muscle are still unknown. The expression by MDSC of the myogenic cell markers desmin and MyoD, in addition to CD34 and Sca-1 and absence of c-kit and CD45, distinguishes these cells from other known adult stem cells such as MSC and MAPC.

We have, in the present study, investigated the identity and anatomical location of muscle-derived stem cells in human skeletal muscle. Our conclusion is that a previously unexplored developmental relationship exists between endothelial and myogenic cells. Indeed, a subset of MDSC express endothelial cell markers, and MDSC spontaneously differentiate into endothelial cells, and/or promote angiogenesis, probably *via* VEGF secretion, following implantation in skeletal and cardiac muscles<sup>9, 13</sup>.

Besides regular satellite cells and endothelial cells, we have identified and characterized a novel population of *myo-endothelial* cells that co-express myogenic and endothelial cell markers. When injected into the injured skeletal muscles of immunodeficient mice, FACS-sorted cells co-expressing myogenic and endothelial cell markers (CD56+CD34+CD144+) regenerated skeletal muscle fibers much more efficiently than conventional CD56+ myogenic cells. Myoendothelial cells clonally expanded from single sorted cells differentiated into myogenic, chondrogenic and osteogenic cells under appropriate culture conditions.

**BODY**

**Previous Results:**

Human skeletal muscle sections were immunostained with antibodies directed against myogenic and endothelial cell antigens. A subset of satellite cells (Pax7+ or CD56+) co-express endothelial cell antigens: VE-cadherin (CD144), vWF, the UEA-1 receptor and CD34. The percentages of Pax7+ cells also expressing these endothelial cell antigens were, respectively, 8.9%, 9.5%, 9.5% and 9.8%, as counted on at least 100 satellite cells in five independent experiments. Co-expression of these molecules by individual cells was ascertained by confocal microscopy. These results suggested the existence within adult human skeletal muscle of a rare subset of cells that co-express myogenic and endothelial cell markers. Adult skeletal muscle samples were then analyzed by flow cytometry after enzymatic dissociation. CD45- viable cells were gated and further separated into CD56+ myogenic cells and CD56- non-myogenic cells. As expected, the latter subset of non-myogenic cells contained the bulk of endothelial cells (CD34+CD144+). However, CD56+ cells also contained a very minor subset of cells expressing CD34 and CD144, thus confirming the existence of cells co-expressing markers of the myogenic and vascular endothelial cell lineages. Using the same immunostaining conditions, we then proceeded to sort the above-described cell subsets by FACS. The mean numbers of viable sorted cells which were recovered per experiment were  $4.8 \pm 1.3 \times 10^4$  CD56+CD34-CD144- myogenic cells,  $7.7 \pm 2.6 \times 10^4$  CD56-CD34+CD144+ endothelial cells and  $1.5 \pm 0.8 \times 10^4$  CD56+CD34+CD144+ myoendothelial cells.

Purities of these three sorted cell populations were, respectively,  $93.8 \pm 1.0 \%$ ,  $92.2 \pm 1.1 \%$  and  $93.5 \pm 1.8 \%$ <sup>14-16</sup>

Myoendothelial, endothelial and satellite cells sorted from adult skeletal muscle were injected intramuscularly, in multiple distinct experiments, into SCID mouse skeletal muscles that had been injured by cardiotoxin. After 10 days, mice were sacrificed and skeletal muscles were analyzed by immunohistochemistry using an antibody directed to human spectrin. All three cell categories tested regenerated spectrin-expressing muscle fibers but quantitative analysis revealed that the regenerative potential of myoendothelial cells is by far the highest. Indeed, 1000 myoendothelial cells generated on average 89 myofibers, as compared with 9 and 5 myofibers produced when the same number of cells expressing exclusively endothelial or myogenic cell markers was injected, respectively. These results support our hypothesis that muscle vascular endothelial cells and a novel subset of cells with an overlapping phenotype between myogenic and endothelial cells are endowed with high muscle regeneration potential<sup>14-16</sup>

Endothelial, myoendothelial and satellite cells were cultured independently in the medium used for MDSC culture<sup>9</sup> for 5 to 6 weeks. All 3 subsets of long-term cultured cells remained capable of differentiating into myotubes *in vitro*. Cultured cells injected into SCID mouse muscles damaged with cardiotoxin also retained their ability to regenerate myofibers, and myoendothelial cells remained the most efficient myogenic progenitors in these assays.

Myoendothelial cells proliferate significantly faster than the two other cell groups. Having previously observed that the high regenerative capacity of mouse MDSC in skeletal and cardiac muscles is related to their resistance to oxidative stress<sup>13</sup>, we treated the three populations under study with hydrogen peroxide in culture. Myoendothelial cells are the most resistant to oxidative stress as indicated by lower levels of cell death under these conditions.<sup>14-16</sup>

We investigated the multipotency of myoendothelial cells, isolated from adult human skeletal muscle, at the single-cell level. Myoendothelial cell clones express markers of myogenic, endothelial, perivascular and mesenchymal stem cells (MSCs). These clonal cells can be differentiated into endothelial cells, smooth muscle cells, pericytes, adipocytes, chondrocytes and osteoblasts *in vitro* and participated in vessel, bone and cartilage regeneration *in vivo*. We therefore demonstrate that human myoendothelial cells possess some fundamental properties of stem cells.<sup>17</sup>

## New Results:

### 1) Identification of CD56<sup>+</sup> CD146<sup>+</sup> UEA-1<sup>+</sup> Cell Population within Cryopreserved Human Skeletal Muscle Cells which Endowed with a High Myogenic Potential *in vivo*

Our recent studies demonstrated that the pure populations of myogenic cells (CD56<sup>+</sup>/CD45<sup>-</sup>CD34<sup>-</sup>CD144<sup>-</sup>), vascular endothelial cells (CD34<sup>+</sup>CD144<sup>+</sup>/CD45<sup>-</sup>CD56<sup>-</sup>) and *myoendothelial* cells (CD56<sup>+</sup>CD34<sup>+</sup>CD144<sup>+</sup>/CD45<sup>-</sup>) can be freshly isolated from adult human skeletal muscle based fluorescence-activated cell sorting (FACS). These human *myoendothelial* cells display a regenerative capacity in skeletal muscles greater than that shown by human cells expressing only the myogenic cell marker CD56 or endothelial cell marker CD34+CD144+<sup>1</sup>. Moreover, we also demonstrated that vascular pericyte-like cells in human skeletal muscle development and regeneration<sup>2</sup>. However, it is not known whether these cells exist in previously cryopreserved human muscle cells and have the same muscle regeneration capacity. In the present study, we used FACS to identify a fraction of cryopreserved primary human muscle cells (passage 4-10) based on expression of the myogenic cell surface marker CD56(NCAM), endothelial cell marker UEA-1(*Ulex Europaeus* Agglutinin I, UEA-1) and pericyte-like cell marker CD146(MCAM, Mel-CAM or MUC18). These populations were sorted and transplanted into cardiotoxin injured skeletal muscles of SCID mice. We hypothesize those myoendothelial cells in primary cultured human skeletal muscle cells still endow with a high myogenic potential, as described in previous studies.

### **Cell isolation and cryopreservation**

9 Human skeletal muscle cells were obtained by enzymatic dissociation of human skeletal muscle (age range 4–76 years; mean age 28 years; 4 female and 5 male). The cells were cultured in proliferation medium<sup>1</sup>. After expansion, the cells were cryopreserved at 2–8 passages and stored at -196°C in liquid nitrogen.

### **Immunohistochemistry staining and Flow cytometry analysis**

The freeze cells were thawed and cultured for 4–10 passages. Human skeletal muscle cells were cytocentrifuged onto glass slides and immunostained. The markers tested for myogenic cells (desmin and CD56) and endothelial cells (CD34, CD144 [VE-cadherin], von Willebrand factor [vWF] and affinity for the UEA-1), pericyte-like cell marker (CD146 and  $\alpha$ -smooth muscle actin [ $\alpha$ -SMA]) were performed. FCM analysis was performed using the following anti-human surface monoclonal antibodies: CD45, CD34, CD144, vWF, KDR, CD56, CD146 and UEA-1.

### **FACS and Immunohistochemistry staining**

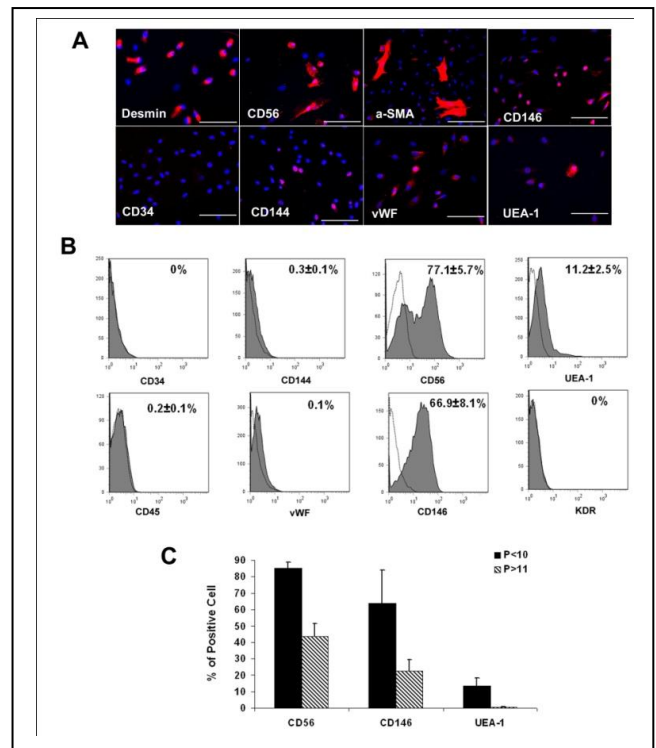
For cell sorting, the cells expressing both myogenic and endothelial markers (myo-endothelial cells, CD56+CD146+UEA-1+/CD45- cells) were sorted using a FACS Aria cell-sorter (BD). Myogenic cells (CD56+/CD45-CD146-UE-1-), endothelial cells (UEA-1+/CD45-CD56-CD146-) and pericyte-like cells (CD146+/CD45-CD56-UEA-1-) also were sorted. 7-amino-actinomycin D (7-ADD) was added to each tube for dead cell exclusion. Sorted cells were re-analyzed by FACS in all experiments and also cytocentrifuged onto glass slides and immunostained for CD56, CD146 and UEA-1 antibody.

### **Cell transplantation:**

The unsorted cultured cells and sorted myogenic cells, pericyte-like cells, endothelial cells, and myoendothelial cells were resuspended in 20  $\mu$ l of HBSS and injected into the cardiotoxin-injured hind-limb muscles of immunodeficient (SCID) mice. Mice were sacrificed 10 days after injection, and the hind-limb muscles were collected for immunohistochemical analysis. Mouse anti-human spectrin (a cytoskeletal protein that has structural homology with dystrophin) was used to stain muscle sections to identify human donor-derived muscle fibers in the mouse muscle.

### **Figure 1: Phenotypic characterization of the cryopreserved human skeletal muscle cells**

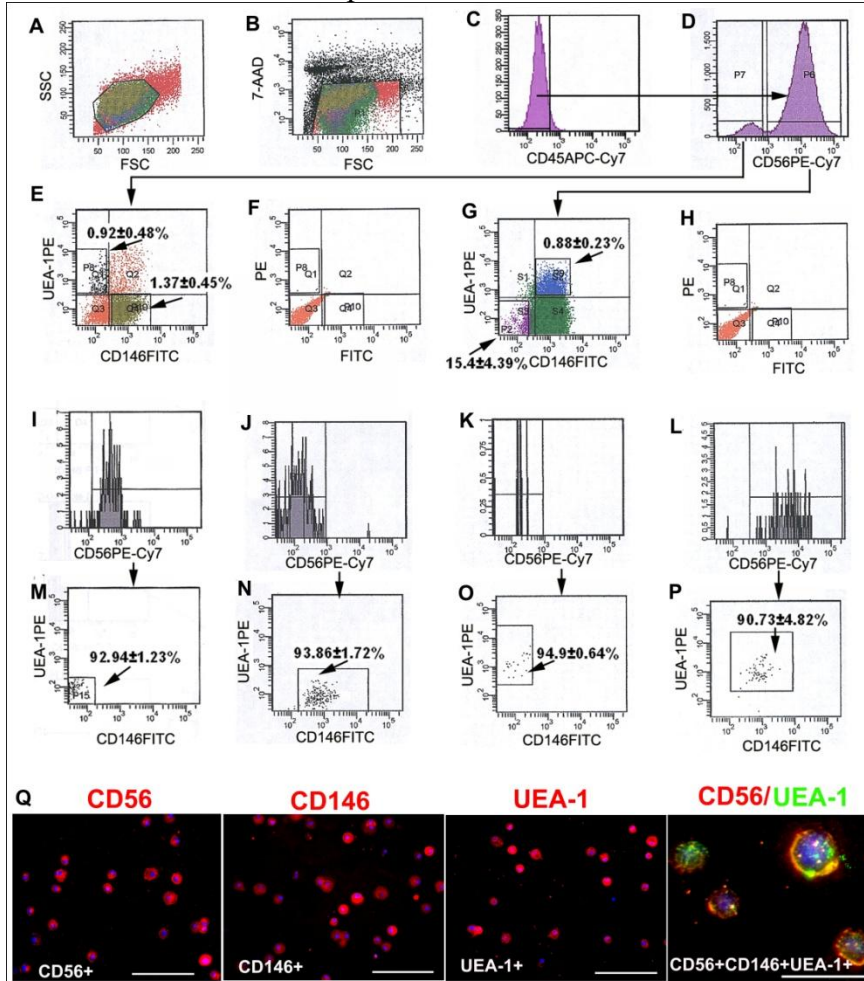
After culturing, cryopreserved muscle cells were cytocentrifuged on glass slides and stained positive for antibodies of desmin, CD56,  $\alpha$ -SMA, CD146, CD144, vWF and UEA-1 and negative for CD34 (1A). Nuclei were stained blue with Dapi. Scale bars, 100  $\mu$ m. Flow cytometric analysis indicated percentage of cryopreserved muscle cells expressing diverse cell surface antigens (1B). CD56, CD146 and UEA-1 expression were decrease when the cells were passaged after 10 (1C).



### **Figure 2: FASCOF human muscle cell subsets**

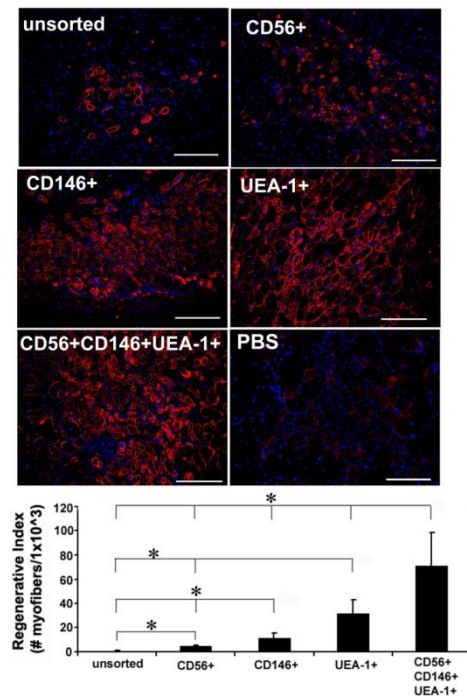
Double-scatter (A) and cell viability (B) gates were set on the whole muscle cell suspension. CD45- cells were selected in order to avoid contamination by hematopoietic cells (C), and further separated into CD56- and CD56+ cells (D). The CD56- cell subset contained both CD146+ (1.37 ± 0.45%) and UEA-1+ (0.92 ± 0.48%) (E) cells, whereas CD56+ cells also contained a minor subpopulation of cells expressing CD146 and UEA-1 (G 0.88 ± 0.23%). Negative (isotype) control for E and G are shown in F and H. In this representative sample,

CD56<sup>+</sup> myogenic cells represented  $15.4 \pm 4.39\%$  (H) of the total cell population. Per experiment, we recovered  $25.61 \pm 9.16 \times 10^4$  CD56<sup>+</sup>/CD45<sup>-</sup>CD146<sup>-</sup>UEA-1<sup>-</sup> myogenic cells, pericyte-like cells (CD146<sup>+</sup>/CD45<sup>-</sup>CD56<sup>-</sup>UEA-1<sup>-</sup>)  $33.54 \pm 20.53 \times 10^4$ , endothelial cells (UEA-1<sup>+</sup>/CD45<sup>-</sup>CD56<sup>-</sup>CD146<sup>-</sup>)  $13.28 \pm 7.37 \times 10^4$  and myoendothelial cells (CD56<sup>+</sup>CD146<sup>+</sup>UEA-1<sup>+</sup>/CD45<sup>-</sup>)  $3.84 \pm 0.96 \times 10^4$ . Purities of these four cell populations were, respectively,  $92.94 \pm 1.23\%$  (I and M),  $93.86 \pm 1.72\%$  (J and N),  $94.9 \pm 0.64\%$  (K and O) and  $90.73 \pm 4.82\%$  (L and P), as indicated by FACS reanalysis. Sorted muscle cells were also cytocentrifuged on glass slides and stained with antibodies to CD56, CD146, UEA-1 (2Q, scale bars, 100  $\mu$ m), and CD56/UEA-1 double staining scale bars, 20  $\mu$ m). Nuclei were stained blue with Dapi.



**Figure 3: Cell transplantation in the mouse muscle**

These cell populations were sorted and transplanted into cardiotoxin injured skeletal muscles of SCID mice (n=7). After 10 days transplantation, anti-human spectrin (a cytoskeletal protein) was used to identify human donor-derived muscle fibers at the injection site. Quantitative analysis of immunohistochemistry results demonstrated that the myogenic regeneration index [human spectrin–positive myofibers per  $1 \times 10^3$  injected cells] was  $0.55 \pm 0.36$  for unsorted cells,  $4.23 \pm 1.16$  for myogenic cells,  $11.44 \pm 3.79$  for pericyte-like cells,  $31.26 \pm 11.57$  for endothelial cells and  $71.23 \pm 27.15$  for myoendothelial cells. CD56<sup>+</sup>CD146<sup>+</sup>UEA-1<sup>+</sup> cells mediated the highest regeneration of spectrin<sup>+</sup> myofibers among the four cell subsets tested (\*  $p < 0.05$ ). UEA-1<sup>+</sup> cells generated more spectrin<sup>+</sup> myofibers than unsorted cells, CD146<sup>+</sup> pericyte-like cells and conventional myogenic cells (\*  $p < 0.05$ ). CD146<sup>+</sup> pericyte-like cells generated more spectrin<sup>+</sup> myofibers than unsorted cells CD56<sup>+</sup> cells (\*  $p < 0.05$ ). CD56<sup>+</sup> myogenic cells generated more spectrin<sup>+</sup> myofibers than unsorted cells (objective x20) (Figures 3, scale bars, 100  $\mu$ m).



We used fluorescence-activated cell sorting (FACS) to identify and isolate 4 different cell populations in cryopreserved human muscle cells by flow cytometry: myogenic cells (CD56<sup>+</sup>/CD45<sup>-</sup>UEA-1<sup>-</sup>CD146<sup>-</sup>), endothelial cells (UEA-1<sup>+</sup>/CD45<sup>-</sup>CD56<sup>-</sup>CD146<sup>-</sup>), pericytes (CD146<sup>+</sup>/CD45<sup>-</sup>CD56<sup>-</sup>UEA-1<sup>-</sup>) and myogenic-endothelial cells (CD56<sup>+</sup>UEA-1<sup>+</sup>CD146<sup>+</sup>/CD45<sup>-</sup>) although the marker expressions decrease after passage 10. These populations were sorted and transplanted into cardiotoxin injured skeletal muscles of SCID mice. In comparison with CD56<sup>+</sup>, UEA-1<sup>+</sup>, CD146<sup>+</sup> only positive cells and total population cells, the CD56<sup>+</sup>CD146<sup>+</sup>UEA-1<sup>+</sup> populations displayed significantly higher muscle regeneration capacity ( $p < 0.05$ ). Taken together, these findings strongly suggested that the existence of distinct populations of cells coexpress myogenic and endothelial cell markers (CD56+CD146+UEA-1+) were identified by immunohistochemistry and flow cytometry within cryopreserved human skeletal muscle cells. These myoendothelial cells have a robust myogenic potential *in vivo* in immunodeficient mice after muscle damage. Further, improvements might allow new approaches to cell-mediated therapies for muscle regeneration and repair.

## 2) Multipotency of adult human myoendothelial cells demonstrated by single-cell-derived clonal populations

We have previously reported that murine muscle-derived stem cells (mu-MDSCs) can differentiate along diverse cell lineages and give rise to endothelial cells, blood cells, bone and cartilage cells<sup>1-5</sup>. In addition, we have demonstrated novel myoendothelial cells in human skeletal muscle that exhibit exceptional myogenic potential in skeletal<sup>6</sup> and cardiac muscle regeneration<sup>7</sup>. Moreover, clonally derived myoendothelial cells can differentiate into myogenic both *in vitro* and *in vivo*<sup>6</sup>. In present study, we investigated whether myoendothelial cells, isolated from adult human skeletal muscle, have the equivalent multipotent features of these mouse MDSCs, i.e. cardiac repair, bone and cartilage formations, both *in vitro* and *in vivo* at the single-cell level.

### **Cells isolation and culturing:**

11 clonally derived myoendothelial cells from 3 human muscle biopsy (30-78y) were sorted on basis of cell-surface markers (CD45<sup>-</sup>CD56<sup>+</sup>CD34<sup>+</sup>CD144<sup>+</sup>) as described previously<sup>6</sup> and plated into 96-well plate at 1 cell per well in proliferation medium (PM) (DMEM, 10%FBS, 10%HS, 1%CEE and 1%P/S). When the cells were grown to 40-50% confluence, the cells from 1 well were plated into 24-well plate, 6-well plate and then 75-cm<sup>2</sup> flasks.

### **Characterization of myo-endothelial cells**



Flow cytometry was performed with the antibodies CD45, NG2, UEA-1, vWF, CD144, CD34, CD146, CD56, CD44 and CD29. For immunocytochemistry staining, we used desmin, m-cadherin and CD56 as myogenic markers; UEA-1, CD144 (ve-cadherin) and vWF as endothelial markers;  $\alpha$ -SMA, NG2 and CD146 as smooth muscle cell and pericyte markers; nestin, neurofilament, GFAP, s-100 and CNpase as neural lineage markers. Western Blot and RT-PCR were also performed.

### ***In vitro and in vivo differentiation of myo-endothelial cells***

Culture-expanded myoendothelial clones were tested for their growth potential and subjected to *in vitro* assays to investigate their multilineage potentials.

**Adipogenic assay in vitro:** Adipogenesis was induced in adipogenic growth medium and evaluated using an Oil Red O stain to indicate intracellular lipid accumulation.

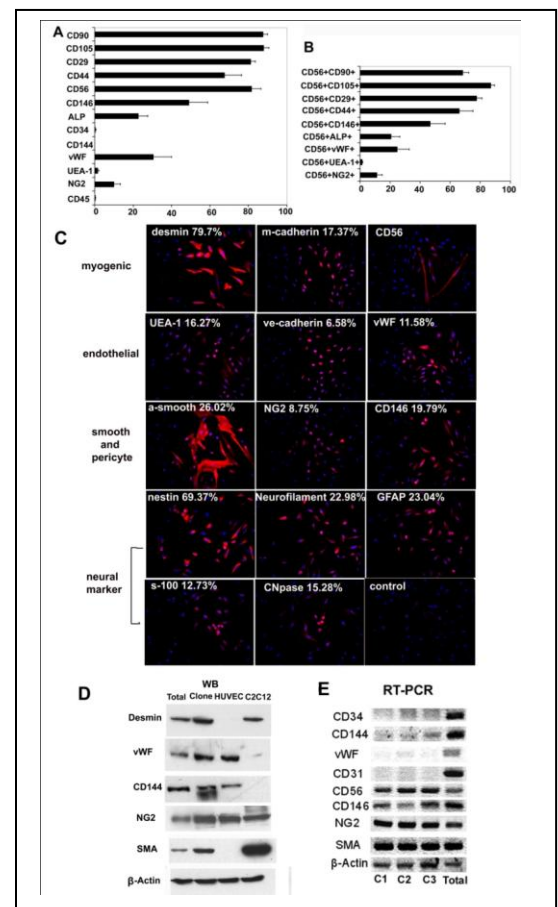
**Cardiac cell differentiation in vitro:** Mouse cardiac cells were mixed at a ration of 1:4 with human myoendothelial clonal cells. The cocultures were maintained in PM for 7 days. After 7 days of culture, the differentiated human myoendothelial cells were detected by immunostaining with antibodies directed against cardiac cell marker, cardiac troponin I (**cTnl**) and human nuclear marker lamin A/C.

**Chondrogenesis assay in vitro:** Pellet cultures were maintained in chondrogenic growth medium. Chondrogenesis was confirmed using the histological stain Alcian Blue. Unsorted total cell populations were cultured under same condition and served as the control.

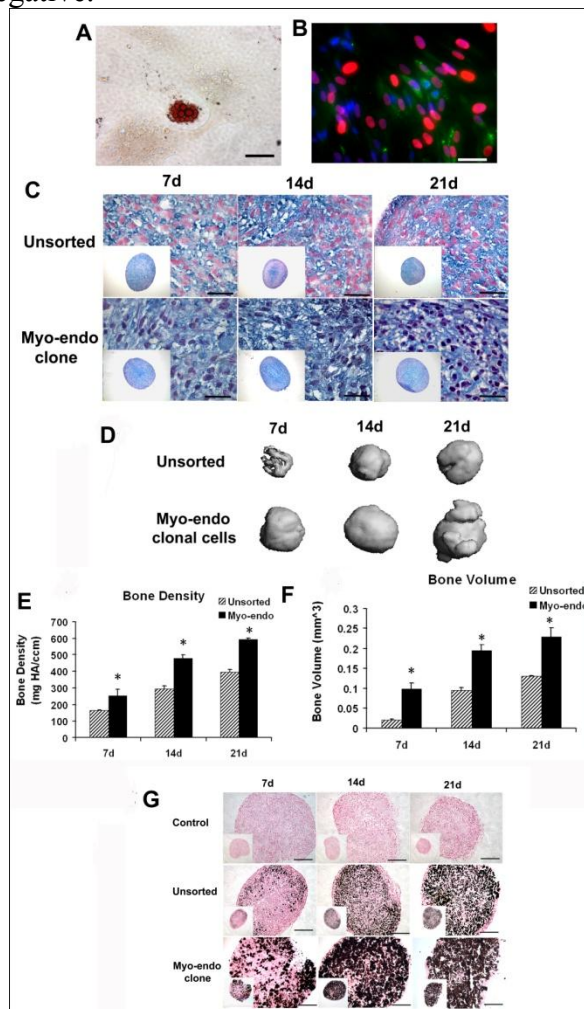
**Osteogenic assay in vitro:** The cell pellets were cultured for up to 3 weeks in osteogenic medium with the supplement of BMP4 (200ng/ml). Samples were scanned by microCT ( $\mu$ CT) and also harvested on day 7, 14 and 21, and then embedded in a paraffin block. Pellet sections were stained with Von Kossa staining. Unsorted total cell populations were cultured in same condition. Myoendothelial clonal cells were maintained in PM to be control.

**In vivo Chondrogenic and osteogenic differentiation:** To assess their multipotency *in vivo*, myoendothelial clones were implanted into the skeletal muscle pocket of SCID mice to test osteogenic and chondrogenic potentials after transduction with retro-BMP4 virus at different time points.

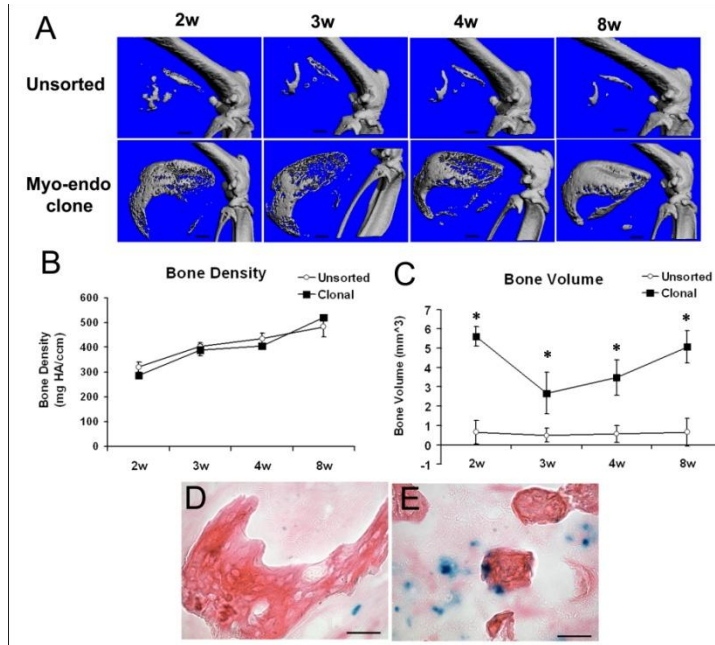
**Fig 1. A-B:** Surface marker profile of clonal myoendothelial cells based FCM analysis. For each marker tested, the percentage of positive cells is expressed as the mean $\pm$ SEM (n=7). **C.** Immunochemistry results indicate that the cells express myogenic markers and spontaneously express endothelial cell, smooth muscle cell, pericyte and neural cell markers. Western blot (**D**) and RT-PCR analysis (**E**) shows that myoendothelial clonal cells can express multiple lineage cell mRNAs (n=3).



**Fig 2 A.** Myoendothelial clone cells were cultured in adipogenic medium differentiated toward the adipogenic lineage within 2 weeks after induction. These cells contained multiple, intracellular, lipid-filled droplets that accumulated Oil Red O. **B.** Under cocultured human myoendothelial clonal cells with mouse cardiac cells for 7 days, immunocytochemistry with antibodies against cTnl (green) and human lamin A/C (red) demonstrated the presence of human nuclei within cardiac cell (green), confirming the fusion of myoendothelial clonal cells with the murine cardiac cells. **C.** Chondrogenic differentiation revealed by Alcian blue/nuclear fast red staining of pellets cultured in chondrogenic medium with the supplement of BMP4 and TGF $\beta$ 3 at different time point. Unsorted cells showed that very few cells can differentiate to chondrocytes. **D.**  $\mu$ CT images showed that myoendothelial clonal cells have a significant bone density and volume compared with unsorted cells under cultured as pellets in osteogenic medium for different time point (**E and F**). **G.** Osteogenic differentiation revealed by Von kossa staining of pellets cultured in the osteogenic medium with the supplement of BMP4 at different time points. Compared with unsorted cells, myoendothelial clonal cells showed that von Kossa staining strong positive at different time points. However, the myoendothelial clonal cells maintained in PM remained von Kossa negative.



**Fig 3 A.** Once retrovirally transduced to express BMP4 and implanted into the intramuscular pocket of SCID mice,  $\mu$ CT scan image demonstrated myoendothelial clonal cells lead to a more consistent and denser ectopic bone formation than unsorted cells at different time points. **B-C.** A greater bone area was found in the myoendothelial clonal cells than the unsorted cells regardless of the bone density. **D.** *In vivo* chondrogenesis by myoendothelial clonal cells was determined by colocalization of round chondrocytes with blue nuclei after staining for *LacZ*/eosin. **E.** *In vivo* osteogenesis was confirmed by colocalization of blue cells in the newly formed bone tissue.



Our study demonstrated that single myoendothelial cell clones can be isolated from human skeletal muscle and that they expressed markers of myogenic (CD56 and desmin), endothelial (CD34, CD144, CD146 and VWF), perivascular ( $\alpha$ -smooth, NG2 and ALP) and mesenchymal stem cells (MSCs) (CD105, CD90, CD29 and CD44) at different level. Interestingly, these single-cell derived clonal populations expressed all know markers of mesenchymal stem cells (MSC) including CD44, CD90 and CD105. Furthermore, these cells can spontaneously differentiate into endothelial cells, smooth muscle cells and pericytes, and neural cells *in vitro*. Our results suggest that myoendothelial may relate to mesenchymal stem cells. More importantly, these cells also differentiated into adipocytes, chondrocytes, osteoblasts and cardiac myocytes under specific conditions *in vitro* and *in vivo*. This suggests that myoendothelial clonal cells may contain more progenitor cells than unsorted muscle cells. We believed that this is the first study to demonstrate a population of clonal myoendothelial human muscle-derived stem cells, co-expressing myogenic and endothelial markers, multipotent at the single-cell level. The potential applications of clonal myoendothelial cells in regenerative medicine are particularly exciting.

## KEY ACCOMPLISHMENTS

1. We have achieved the molecular identification and sorting of human myo-endothelial cells.
2. We have regenerated skeletal muscle with human myoendothelial cells
3. We have cultured myoendothelial cells over the long term, and shown that these proliferate faster, and survive better under oxidative stress than myogenic cells and endothelial cells
4. We have shown that myoendothelial cells are, at the clonal level, multi-lineage mesodermal stem cells
5. We Identified a CD56<sup>+</sup> CD146<sup>+</sup> UEA-1<sup>+</sup> Cell Population within Cryopreserved Human Skeletal Muscle Cells which Endowed with a High Myogenic Potential *in vivo*



## **6. We have shown the multipotency of adult human myoendothelial cells from single-cell-derived clonal populations**

### **REPORTABLE OUTCOMES**

- Peault, B. et al. Stem and Progenitor Cells in Skeletal Muscle Development, Maintenance, and Therapy. *Mol Ther* (2007)
- Zheng, B., Cao, B., Crisan, M., Sun, B., Li, G.H., Logar, A., Yap, S., Pollett, J.B., Drowley, L., Cassino, T., Gharaibeh, B., Deasy, B., Huard, J., Péault, B. Prospective identification of myogenic endothelial cells in human skeletal muscle. *Nature Biotechnology*, 25(9):1025-1034 (2007)
- Crisan, M., Deasy, B., Gavina, M., Zheng, B., Huard, J., Lazzari, L., Péault, B. Purification and long-term culture of multipotent progenitor cells affiliated with the walls of human blood vessels: myoendothelial cells and pericytes. *Methods In Cell Biology*, 86:295-309. (2008)
- Crisan M, Huard J, Zheng B, Sun B, Yap S, Logar A, Giacobino JP, Casteilla L, Peault B. Purification and culture of human blood vessel-associated progenitor cells. *Curr protoc stem cell* 2008 Mar; Chap 2: Unit 2B.2.1-2B.2.13
- Crisan M, Park, TS Casteilla, L, Sun B, Zheng B, Yap S, Norotte C, Corselli M, Traas J, Deasy B, Andriolo G, Bühring HJ, Lazzari L, Giacobino JP, Huard J, Péault B. Perivascular origin of mesenchymal stem cells in multiple human tissues. *Cell Stem Cell*, 2008 Sep 11;3(3):301-13
- Bo Zheng, Guangheng Li, Alison Logar, Bruno Peault and Johnny Huard. Identification of CD56<sup>+</sup> CD146<sup>+</sup> UEA-1<sup>+</sup> Cell Population within Cryopreserved Human Skeletal Muscle Cells which Endowed with a High Myogenic Potential in vivo. *Under revision in Cell Transplantation*
- Zheng, B; Li, G H; Okada, M; Sun, B; Deasy, BM; Pollet, JB; Logar, A; Peault, B; Huard, J Multipotency of adult human myoendothelial cells demonstrated by single-cell-derived clonal populations. *Under revision J of Mol Cell Biology*

Although the present project has been focused on the regeneration of *skeletal* muscle, we have also documented the strong potential of these cells to regenerate the myocardium and improve cardiac function post-infarction:

- Okada, M., Payne, T., Zheng, B., Oshima, H., Momoi, N., Tobita, K., Keller, B.B., Phillippi, J., Péault B., Huard, J. Improved cellular cardiomyoplasty via human myogenic-endothelial cells identification of a progenitor cell population from human skeletal muscle that is superior to committed skeletal myoblasts for cardiac cell therapy. *Journal of the American College of Cardiology*. (2008)

### **CONCLUSIONS**

The experiments performed in this project have provided evidence for the existence of a strong myogenic potential in cells related to the endothelial cell lineage in the normal, human adult skeletal muscle, and therefore suggest a developmental relationship between vascular cells and myogenic cells. We have indeed confirmed the existence of a novel population of cells present between human muscle fibers that co-express the nuclear Pax7 myogenesis-specific transcription factor and surface antigens that typify endothelial cells: VE-cadherin (CD144) and vWF.

The leading conclusion of the present work is that human muscle-derived myoendothelial cells can regenerate skeletal muscle, quantitatively more efficiently than regular myogenic (satellite) cells. The higher regeneration capacity exhibited by myoendothelial cells is due in part to better resistance to oxidative stress, a likely environmental condition within the injured skeletal muscle. These data suggest the existence of a novel hierarchy within human adult skeletal muscle along which vascular endothelial cells give rise to early myogenic stem cells, which in turn replenish the satellite cell population.

These novel myogenic progenitors are amenable to biotechnological processing; these cells can be sorted to homogeneity by flow cytometry from skeletal muscle, then cultured clonally on the long term, with no major loss of developmental potential, in basic medium, where they proliferate rapidly but do not become tumorigenic. Therefore, the transplantation of such autologous endothelium-related progenitors could be envisioned shortly as a therapy of skeletal muscle diseases and injuries.

## REFERENCES

1. Bischoff, R. Proliferation of muscle satellite cells on intact myofibers in culture. *Dev Biol* 115, 129-139 (1986).
2. Bischoff, R. in *Myology: Basic and Clinical* 97-118 (McGraw-Hill, New York; 1994).
3. Skuk, D. & Tremblay, J.P. Myoblast transplantation: the current status of a potential therapeutic tool for myopathies. *J Muscle Res Cell Motil* 24, 285-300 (2003).
4. Partridge, T.A. Invited review: myoblast transfer: a possible therapy for inherited myopathies? *Muscle Nerve* 14, 197-212 (1991).
5. Menasche, P. et al. Myoblast transplantation for heart failure. *Lancet* 357, 279-280 (2001).
6. Cao, B., Deasy, B.M., Pollett, J. & Huard, J. Cell therapy for muscle regeneration and repair. *Phys Med Rehabil Clin N Am* 16, 889-907, viii (2005).
7. Menasche, P. Cellular transplantation: hurdles remaining before widespread clinical use. *Curr Opin Cardiol* 19, 154-161 (2004).
8. Miller, J.B., Schaefer, L. & Dominov, J.A. Seeking muscle stem cells. *Curr Top Dev Biol* 43, 191-219 (1999).
9. Qu-Petersen, Z. et al. Identification of a novel population of muscle stem cells in mice: potential for muscle regeneration. *J Cell Biol* 157, 851-864 (2002).
10. Gussoni, E. et al. Dystrophin expression in the mdx mouse restored by stem cell transplantation. *Nature* 401, 390-394 (1999).
11. Partridge, T.A. Stem cell therapies for neuromuscular diseases. *Acta Neurol Belg* 104, 141-147 (2004).
12. Peault, B. et al. Stem and Progenitor Cells in Skeletal Muscle Development, Maintenance, and Therapy. *Mol Ther* (2007).
13. Oshima, H. et al. Differential myocardial infarct repair with muscle stem cells compared to myoblasts. *Mol Ther* 12, 1130-1141 (2005).
14. Zheng, B., Cao, B., Crisan, M., Sun, B., Li, G.H., Logar, A., Yap, S., Pollett, J.B., Drowley, L., Cassino, T., Gharaibeh, B., Deasy, B., Huard, J., Péault, B. Prospective identification of myogenic endothelial cells in human skeletal muscle. *Nature Biotechnology*, 25(9):1025-1034 (2007)
15. Crisan, M., Deasy, B., Gavina, M., Zheng, B., Huard, J., Lazzari, L., Péault, B. Purification and long-term culture of multipotent progenitor cells affiliated with the walls of human blood vessels: myoendothelial cells and pericytes. *Methods In Cell Biology*, 86:295-309. (2008)
16. Crisan, M., Zheng, B., Sun, B., Yap, S., Logar, A., Huard, J., Giacobino, J.P., Casteilla, L., Péault, B. Purification and culture of human blood vessel-associated progenitor cells. *Current Methods in Stem Cell Biology*. In Press.
17. Zheng, B., Li, G., Deasy, B., Pollett, J., Sun, B., Drowley, L., Gharaibeh, B., Usas, A., Logar, A., Peault, B., and Huard, J. The myoendothelial cell: a novel stem cell from adult human skeletal muscle. *In preparation*

**Project # 4 Final Report**  
**Cell therapy for muscle regeneration advances via**  
**interdisciplinary-driven regenerative medicine (iDREAM)**  
**(Bridget Deasy)**

**Key Research Accomplishments**

**1. Technical Objective #1: Use preplate isolation technique and a bioinformatic cell culture system to screen adult human stem cell candidates for their muscle regeneration potential.** We identified that the most potent human muscle stem cell candidate can be isolated from slowly adhering fractions of the cell suspension which derives from the muscle biopsy. These results were included in several publications, most notably in a recently accepted study to *Tissue Engineering*. Future studies: We have new experiments to determine if there is an even more potent subpopulation of stem cells within the muscle stem cell population. This new set of experiments and line of study is the focus of a pending NIH grant application.

**2. Technical Objective #2: Test culture conditions for extensive and long-term expansion of human myogenic cells to preserve the cells' phenotype and regeneration efficiency.** We have determined that human MDSCs have reduced expandability as compared to mouse cells. Further, we find that the human MDSC candidate undergoes phenotypic changes quickly in culture. Future studies: We ongoing experiments to determine if the small molecule drug can further improve the ex vivo expandability and maintenance of the phenotype. This new set of experiments and line of study is the focus of pending NIH grant applications

**Supplemental Aims**

**1. Technical Objective #1: Use a bioinformatic LCI culture system to test the effect of temperature on the processing of MDSC from skeletal muscle biopsy.**

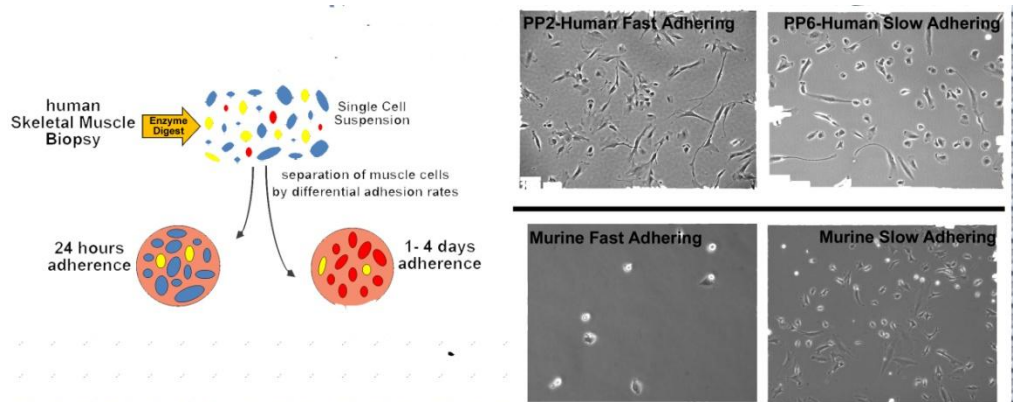
We determined that our yield or number of stem cells harvested is reduced when the muscle biopsy is stored at 4C for up to 1 week. The greatest yield appears to be from biopsies that are minimally stored for up to 24 hours. These results have not been published. Future studies: We would like to further examine these effects of biopsy handling, however these studies are not currently underway.

**2. Technical Objective #2: To test the effect of various cyroprotectant agents and procedures on the stem cell phenotype of human MDSC.**

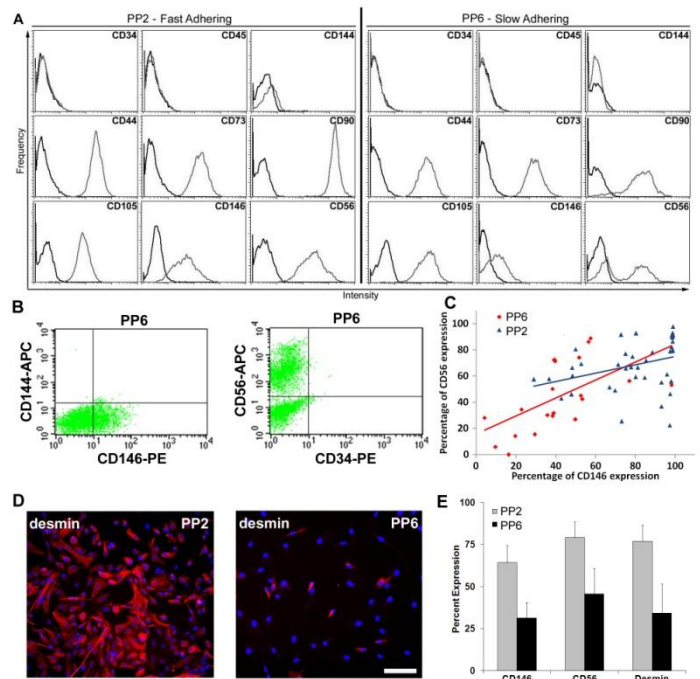
We determined that 10% DMSO is the optimal freezing media, among those compared, to yield the highest post-thaw viability. However, thawed muscle cells lose their expression of protein markers CD56 and CD146. These results have not been published. Future studies: We have experiments underway to examine if a small molecule drug can further improve the cryopreservation and maintenance of the phenotype. This new set of experiments, and line of study is the focus of pending NIH grant applications.

**Key Project Findings:**

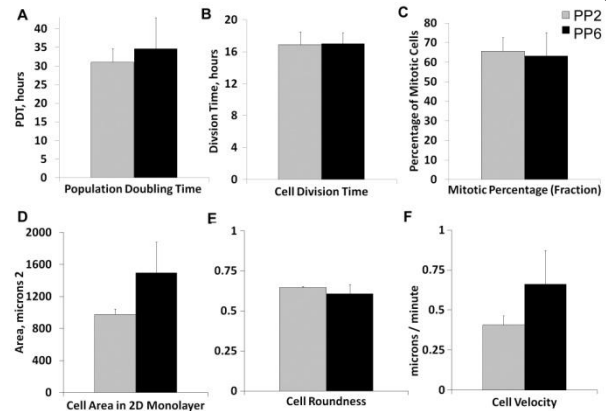
- 1) After separation of single cell isolates by adherence rates, two main populations are acquired: PP2, fast adhering cells and PP6, slow adhering cells. Figure 1.



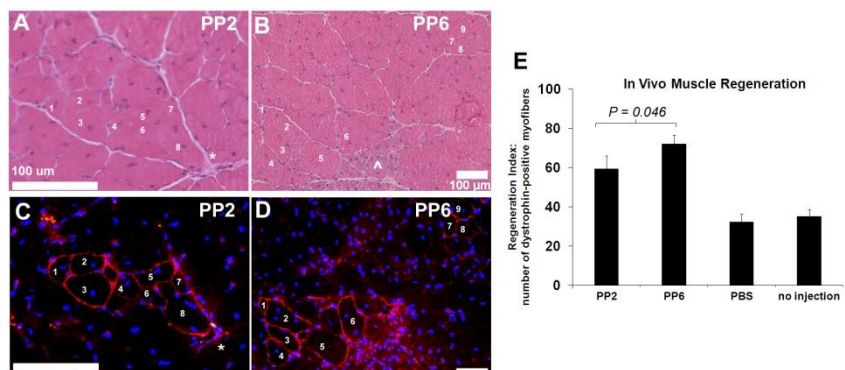
- 2) *In vitro* comparison of PP2 and PP6 muscle derived populations. **(A)** Flow cytometric histograms for PP2 and PP6 populations; cells are negative for CD34, CD45, and CD144, highly positive for CD44, CD73, CD90, & CD105, and exhibit variable expression of CD56 & CD146. **(B)** Flow cytometry dot plots of expression of CD146 and CD56 in slowly adhering populations. The low level of CD146 is visible on the dot plot (CD144 is also shown here), while 2 distinct populations of CD56[+] and CD56[-] cells are visible on the plot (separate plot with CD34 expression). **(C)** For both PP6 and PP2 populations, there is a significant positive correlation between the level of expression of CD146 and the myogenic marker CD56. **(D)** Immunocytochemistry for desmin expression (red), with Hoechst-labelled nuclei (blue). **(E)** Mean *in vitro* expression of CD56 (flow), CD146 (FACS) and desmin (immunocytochemistry) for PP2 and PP6 populations. (Figure 2)



- 3) Human muscle stem cell characteristics. **(A-C)** Growth characteristics of PP2 and PP6 described by **(A)** population doubling time (PDT), **(B)** division time (DT), and **(C)** mitotic fraction. There were no significant differences in the growth rates between the different fractions, however the PP6 population had a slight trend toward slower population doubling time (35 hours) as compared PP2 populations (30 hours). **(D-F)** In vitro morphology and migration analysis. PP2 and PP6 cells described by mean cell area or spreading, circularity, and centroid velocity. PP2 cells were significantly larger than PP2 cells, but showed no difference in cell shape or cell roundness. We also found that PP2 were significantly, less migratory than PP6 (as measured by cell velocity Figure 3).



- 4) *In vivo* cell participation in muscle regeneration. **(A & B)** Hematoxylin and eosin stain of transplantation site for PP2 and PP6 populations. Serial section of polyclonal dystrophin antibody **(C & D)**; fluorescent images demonstrate dystrophin positive fibers at 2 weeks post transplantation with PP2 and PP6. **(E)** Quantification of the level of skeletal muscle



regeneration is measured as the regeneration index – number of dystrophin positive fibers per 10<sup>5</sup> transplanted donor cells per muscle section. We observe significantly more dystrophin-positive myofibers after PP6 transplantation as compared to PP2 and sham transplantation. Scale bar represents 100  $\mu$ m. (Figure 4).

## Reportable Outcomes

### Publications which have resulted from this work:

1. Chirieleison SM, Schugar RC, Deasy BM. 2008. Current Progress in Cell-mediated Gene Therapy for Muscular Dystrophies. *Research Advances in Gene Therapy*. Global Research Network. Ed. RM Mohan.
2. Schugar, RC, Robbins, PD, and Deasy BM. 2008. Small molecules in stem cell self-renewal and differentiation. *Gene Therapy*. 15(2):126-35.
3. Schmidt, BT, Feduska, JM, Witt, AM, and Deasy BM. 2008 Robotic cell culture system for stem cell assays. *Industrial Robot*. 35 (2):116-124.
4. Deasy, BM, Feduska, JM, Payne, TR, Ambrosio, F, Ly, Y, and J Huard. 2009. Effect of VEGF on the Regenerative Capacity of Muscle Stem Cells in Dystrophic Skeletal Muscle. *Mol Therapy*. doi:10.1038/mt.2009.136.
5. RC Schugar, SM Chirieleison, KE Wescoe, JJ Nance, Y Askew, BT Schmidt, JM Evron, B Peault and BM Deasy. 2009. In situ Identification of CD146 Stem Cells in Primitive Human Umbilical Cord Stroma with High Isolation Yield, High Expansion and Phenotype Stability for Regenerative Therapies. *Journal of Biomedicine and Biotechnology*. Volume 2009, Article ID 789526, doi:10.1155/2009/789526.
6. **Deasy, BM\*, Chirieleison SM, Witt, AM, Peyton, MJ, Bissell, TA.** 2010. Tracking stem cell function with computers via live cell imaging: Identifying donor variability in human stem cells. *Operative Techniques in Orthopedics*. 20 (2):127-135. \* *corresponding author*.
7. Deasy, B.M. *Asymmetric Behavior of Stem Cells*. 2008. Chapter 2. *Regulatory Networks in Stem Cells*. Humana /Springer Press.
8. Chirieleison, SM, Scelfo, CC, Bissell, TA, Anderson, JE, Koebler, D, Yong Li, Deasy, BM. Robotic imaging systems for biological study of dynamic cell behavior., 2010 *ACCEPTED Biotechnology Progress*.
9. **Chirieleison SM**, Feduska JM, Schugar RC, Sanford SL, Scelfo CC, Askew Y, Deasy BM. 2009. Human Muscle-Derived Cells Isolated by Differential Adhesion Rates Exhibit Differences in Phenotype and Contribution to Skeletal Muscle Regeneration in mdx/SCID model. *ACCEPTED Tissue Engineering*.

### Abstracts (Sample of > 40 abstracts that have resulted from this work) :

1. Human Muscle-Derived Cells Isolated By Differential Adhesion Rates Exhibit Differences in Phenotype and Contribution to Skeletal Muscle Regeneration in Mdx/SCID Model. Chirieleison, S M; <sup>1</sup>Feduska, J M; <sup>1</sup>Schugar, R C <sup>1</sup>Askew, Y. <sup>1-3</sup> Deasy, B M. Orthopedic Research Society. 2011. Long Beach, CA POSIUM/POSTER
2. Methods to Identify and Isolate Quiescent Human Muscle Derived Stem Cells <sup>12</sup>Bissell, T A; <sup>1,2</sup> Chirieleison S C; <sup>1,2</sup>Witt, M; <sup>1,2</sup>Kilne, D; <sup>1-3</sup>Deasy, B M. Orthopedic Research Society. 2011. Long Beach, CA
3. Deasy, BM, Bissell, TA, Chirieleison, SM, Piganelli JD. Ex Vivo Expanded Human Muscle Stem Cells show increased levels of reactive oxygen species and increased sensitivity to oxidative stress. The Ottawa Conference on New Directions in Biology and Disease of Skeletal Muscle 2010.
4. Chirieleison SM, Witt AM, Flythe S, Deasy BM. 2009. Live Automated Cell Imaging, Examination of Human Stem Cell Population Dynamics Under Growth Factor Treatment. *Midwest Tissue Engineering Consortium*; Pittsburgh, PA, USA. *PODIUM*

5. **Chirieleison SM** , Scelfo CC, Askew Y, Deasy BM. 2008. Development of Morphological Measurement Scheme Using Open Source Software for Live Cell Imaging Approaches to Stem Cell Biology. University of Pittsburgh Science 2008; Pittsburgh, PA, USA. POSTER
6. **Chirieleison SM** , Scelfo CC, Deasy BM. 2008. Quantitative Analysis of Therapeutic Muscle Cell Populations through Live Automated Cell Imaging. American Society for Cell Biology Annual Meeting; San Francisco, CA, USA. POSTER
7. **Chirieleison SM** , Scelfo CC, Askew Y, Deasy BM. 2008. Development of Morphological Measurement Scheme Using Open Source Software for Live Cell Imaging Approaches to Stem Cell Biology. Pittsburgh Orthopaedic Journal; Pittsburgh, PA, USA.
8. Scelfo CC, **Chirieleison SM** , Deasy BM. 2008. Integration and Adaptation of Live Cell Image Analysis. Pittsburgh Orthopaedic Journal; Pittsburgh, PA, USA.
9. **Chirieleison SM** , JM Feduska, RC Schugar, SL Sanford, J Huard, BM Deasy. 2008. Identifying Populations of Human Muscle Derived Stem Cells to Participate in Skeletal Muscle Regeneration Based on Phenotypic Differences. Pittsburgh Orthopaedic Journal; Pittsburgh, PA, USA.
10. **Chirieleison SM** , Feduska JM, Schugar RC, Witt AM, Deasy BM. 2008. In Vitro Aging of Human Muscle Stem Cells Due to Culture Expansion. International Society for Stem Cell Research; Philadelphia, PA, USA. POSTER
11. **Chirieleison SM** , Scelfo, CC, Askew Y, Deasy BM. 2008. Development of Morphological Measurement Scheme Using Open Source Software for Live Cell Imaging Approaches to Stem Cell Biology. International Society for Stem Cell Research, Philadelphia, PA, USA. POSTER
12. **Chirieleison SM** , Feduska JM, Schugar RC, Sanford SL, Huard J, and Deasy BM. 2008. Identifying Regenerative Populations of Human Muscle-Derived Cells and Tracking Phenotypic Changes in Culture. MidWest Tissue Engineering Consortium. Cincinnati, OH, USA. PODIUM
13. **Chirieleison SM** , Feduska JM, Schugar RC, Sanford SL, Huard J, Deasy BM. 2008. Identifying Populations of Human Muscle Derived Stem Cells to Participate in Skeletal Muscle Regeneration Based on Phenotypic Differences. Orthopaedic Research Society; San Francisco, CA, USA. POSTER



**Project # 5 Final Report\*\***  
**Inhibiting cell death and promoting muscle growth for congenital muscular dystrophy**  
**(Xiao Xiao)**

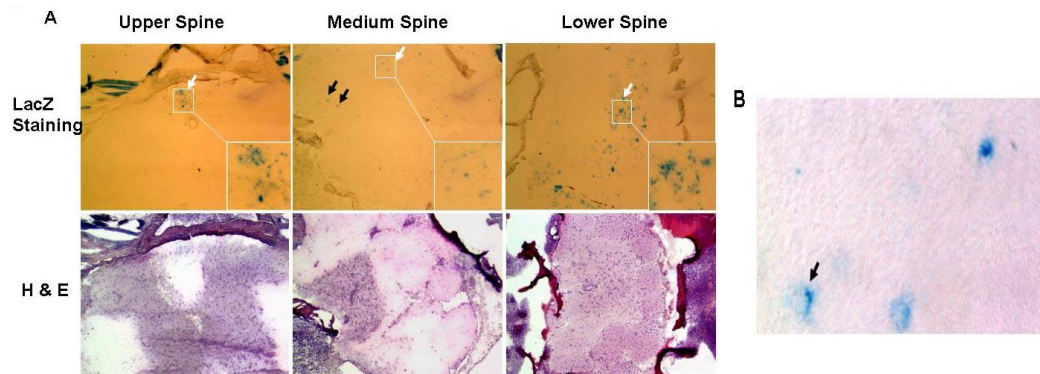
**\*\*Note that no additional work has been performed on this project. The final report for this project was written in the 2009 Progress report. The information provided below is simply a reiteration of that report.**

## Introduction

Congenital muscular dystrophy (CMD) is a group of severe forms of muscular dystrophy leading to early death in human patients(1-3, 7). The majority of cases are caused by genetic mutations in the major laminin, laminin containing the  $\alpha 2$  chain (formerly named merosin), in the muscle basement membrane(4, 6, 8, 11). The early morbidity/fatality and the lack of effective treatment require urgent search for novel therapeutics. Previously, we utilized mini-agrin, which has been proven to have a therapeutic effect in transgenic MCMD mice, to treat MCMD mice by AAV vector(10). Our preliminary studies showed that over-expression of mini-agrin protein greatly improved general health and muscle morphology in MCMD mice. However, the treated disease mice still developed gradual paralysis and displayed shorter life span than wild type mice. To further improve the current gene therapy paradigm, we have developed complementary gene therapy strategy for laminin alpha2-deficient CMD.

## Body

As mentioned earlier, we utilized laminin alpha2 deficient congenital muscular dystrophy (MDC1A), a severe form of muscular dystrophy animal model, as our muscle injury model in this proposal. We evaluated the therapeutic effects of delivering different molecules, such as insulin-like growth factor 1 (IGF-1), anti-apoptotic gene BCL-XL, as well as myostatin propeptide, on muscle and nerve pathogenesis of MDC1A. While we did not observe the significant therapeutic effects by single delivery of those factors on MDC1A mice, we made very interesting discovery during those experiments and wrapped up two manuscripts. Since the first manuscript



**Figure 1. LacZ staining of spinal cord from AAV8-LacZ injected mice. A. LacZ positive cells in white matter.** The vector was delivered on 3-day-old neonatal mice, and the mice were sacrificed at 2-month-old age. Notably, most of the lacZ positive spots were in white matter (white arrow), and very few LacZ positive cells were in grey matter (black arrow). Insets were indicated enlarged area. The consecutive sections of H&E staining were used to display the structure of spinal cord. It was also apparent that there were more LacZ positive cells in lower spine, followed by medium spine, and then upper spine. B. Few LacZ positive cells in grey matter. Button-like structure (black arrow ) in grey matter indicated small neuron and axon communication.

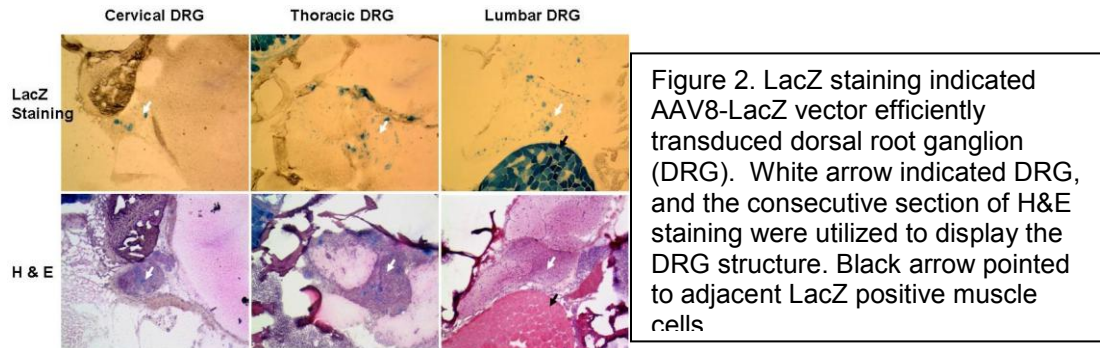
has been published {Qiao, 2008 #980}, we will mainly concentrate on the second manuscript in this report.

AAV vector transduced white matter of spinal cord

Previously, we have revealed that delivering AAV serotype 8 vectors to neonatal mice can efficiently transduce whole-body skeletal muscle and cardiac muscle. In the present study, we utilized the same AAV serotype and similar delivery route to investigate the ability of AAV vector to infect peripheral nervous system and spinal cord. For the first

set of study, we utilized AAV8-CMV-LacZ vector. Two months after vector injection, the mice were sacrificed. The whole spine including bone and adjacent muscle were cut into three pieces and quick-frozen away. After

cryo-section, the slides were subjected to LacZ staining, and H& E staining were performed on the consecutive sections to display the histology. As shown in figure 1A, most LacZ positive cells were located in white matter in the spinal cord of AAV8-LacZ delivered mice (white arrow and inset area). Occasionally, we could see few LacZ positive cells in grey matter (black arrow and figure 1B). Notably, there were more LacZ positive cells in the lower spine and less LacZ positive cells in the higher spine portion. Large magnification of few LacZ positive cells in grey matter of ventral horns showed button-like structures in close proximity and overlapping neuronal cells (Fig 1B). AAV8 vector effectively transduced dorsal root ganglion and peripheral nerves



In addition to the white matter, we noticed AAV8 vector could efficiently infect dorsal root ganglion (DRG) cells which were positioned outside of the spinal cord (Fig2 and Fig 3, white arrow). Across the whole spine,

all the DRG neuronal cells were effectively transduced by AAV vector (Fig.2).

In the second set of our study, we wished to use a different report gene, such as GFP gene, to further prove our finding. Similar to LacZ vector, AAV8-D(+)-CMV-GFP vector was delivered into neonatal mice. Two months after vector injection, the mice were sacrificed. To reduce the background staining of spinal cord, we did perfusion to remove circulating blood and fixed with 4% paraformaldehyde (under anesthesia) when the mice were sacrificed. Figure 3 displayed middle portion of the spine, most of the GFP positive cells were located in white matter of spinal cord and DRG (white arrow).

Except for white matter of spinal cord and DRG, we also observed LacZ and GFP positive cells in peripheral nerve fibers (Fig 4).

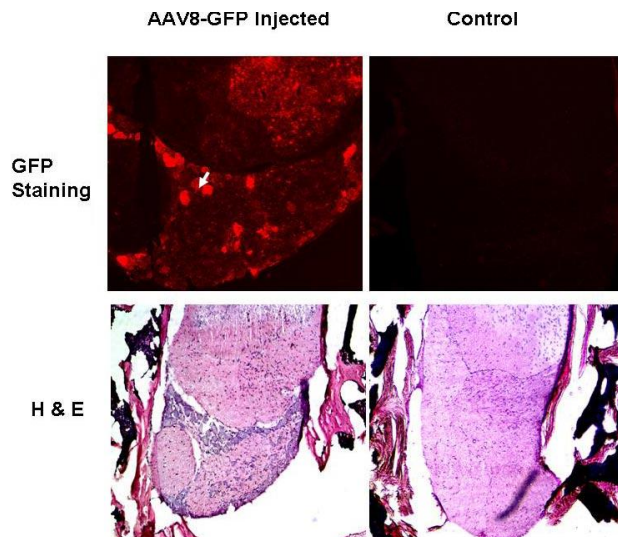


Figure 3. Immunofluorescent staining of GFP in spinal cord and dorsal root ganglion from AAV8-GFP delivered mice.

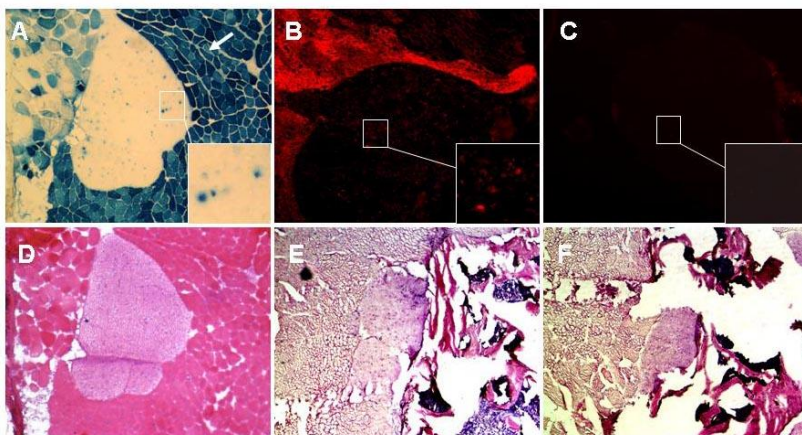


Figure 4. AAV vector efficiently transduced peripheral nerve roots. A was from AAV8-LacZ injected mice, and B was from AAV8-GFP injected mice, C was from mock injected animal but stained with GFP. D, E, F were consecutive section of H& E staining. Insets were indicated enlarged area of peripheral nerves. The LacZ positive cells surrounding peripheral nerves in picture A (white arrow) were muscle cells.



## Key Research Accomplishments:

1. We have delivered myostatin propeptide gene into laminin alpha2-deficient CMD mice and the therapeutic effect was evaluated. Unlike mdx mice for which myostatin propeptide delivery can ameliorate its muscle pathology, the delivery of propeptide had a severe side effect on laminin alpha2-deficient CMD mice. The injected mice died even early than untreated controls. This phenomenon is consistent with previous discovery(5).
2. We have delivered AAV-IGF1 vector into laminin alpha2-deficient CMD mice and did not observe significant therapeutic effect.
3. We have delivered AAV-BCL-XL into laminin alpha2-deficient CMD mice and did not observe significant therapeutic effect.

## Reportable Outcomes:

Our manuscript entitled “Myostatin propeptide gene delivery by AAV8 vectors enhances muscle growth and ameliorates dystrophic phenotypes in *mdx* mice” has been published in Human Gene Therapy 2008 Mar; 19(3): 241-54(9).

Our second manuscript titled “Efficient gene transfer to dorsal root ganglion and peripheral nerves via systemic delivery of AAV vectors” is in preparation and will be submitted soon.

## Conclusions:

Single AAV-IGF1, AAV-Bcl-XL, or AAV-MPRO gene delivery can not offer therapeutic benefit for laminin alpha 2 deficient *dy<sup>w</sup>/dy<sup>w</sup>* mice.

AAV can efficiently transduce peripheral nervous system and dorsal root ganglion cells.

## References

1. **Allamand, V., and P. Guicheney.** 2002. Merosin-deficient congenital muscular dystrophy, autosomal recessive (MDC1A, MIM#156225, LAMA2 gene coding for alpha2 chain of laminin). Eur J Hum Genet **10**:91-4.
2. **D'Alessandro, M., I. Naom, A. Ferlini, C. Sewry, V. Dubowitz, and F. Muntoni.** 1999. Is there selection in favour of heterozygotes in families with merosin-deficient congenital muscular dystrophy? Hum Genet **105**:308-13.
3. **Emery, A. E.** 2002. The muscular dystrophies. Lancet **359**:687-95.
4. **Kuang, W., H. Xu, P. H. Vachon, L. Liu, F. Loechel, U. M. Wewer, and E. Engvall.** 1998. Merosin-deficient congenital muscular dystrophy. Partial genetic correction in two mouse models. J Clin Invest **102**:844-52.
5. **Li, Z. F., G. D. Shelton, and E. Engvall.** 2005. Elimination of myostatin does not combat muscular dystrophy in dy mice but increases postnatal lethality. Am J Pathol **166**:491-7.
6. **O'Brien, D. P., G. C. Johnson, L. A. Liu, L. T. Guo, E. Engvall, H. C. Powell, and G. D. Shelton.** 2001. Laminin alpha 2 (merosin)-deficient muscular dystrophy and demyelinating neuropathy in two cats. J Neurol Sci **189**:37-43.
7. **Pegoraro, E., M. Fanin, C. P. Trevisan, C. Angelini, and E. P. Hoffman.** 2000. A novel laminin alpha2 isoform in severe laminin alpha2 deficient congenital muscular dystrophy. Neurology **55**:1128-34.
8. **Pegoraro, E., H. Marks, C. A. Garcia, T. Crawford, P. Mancias, A. M. Connolly, M. Fanin, F. Martinello, C. P. Trevisan, C. Angelini, A. Stella, M. Scavina, R. L. Munk, S. Servidei, C. C. Bonnemann, T. Bertorini, G. Acsadi, C. E. Thompson, D. Gagnon, G. Hoganson, V. Carver, R. A.**

- Zimmerman, and E. P. Hoffman.** 1998. Laminin alpha2 muscular dystrophy: genotype/phenotype studies of 22 patients. *Neurology* **51**:101-10.
9. **Qiao, C., J. Li, J. Jiang, X. Zhu, B. Wang, J. Li, and X. Xiao.** 2008. Myostatin Propeptide Gene Delivery by Adeno-Associated Virus Serotype 8 Vectors Enhances Muscle Growth and Ameliorates Dystrophic Phenotypes in mdx Mice. *Hum Gene Ther* **19**:241-54.
10. **Qiao, C., J. Li, T. Zhu, R. Draviam, S. Watkins, X. Ye, C. Chen, J. Li, and X. Xiao.** 2005. Amelioration of laminin- $\alpha$ 2-deficient congenital muscular dystrophy by somatic gene transfer of miniagrin. *Proc Natl Acad Sci U S A*.
11. **Tome, F. M., T. Evangelista, A. Leclerc, Y. Sunada, E. Manole, B. Estournet, A. Barois, K. P. Campbell, and M. Fardeau.** 1994. Congenital muscular dystrophy with merosin deficiency. *C R Acad Sci III* **317**:351-7.

**Project # 6 Final Report\*\***  
**Treatment for Muscle Wasting**  
**(Paula Clemens)**

**\*\*Note that no additional work has been performed on this project. The final report for this project was written in the 2009 Progress report. The information provided below is simply a reiteration of that report.**

**Introduction:**

The ability to promote muscle regeneration in the setting of focal or generalized muscle loss could confer significant clinical benefit in the setting of focal neuropathic or other processes that cause muscle atrophy or chronic illnesses that cause cachexia. We hypothesize that gene transfer strategies can promote muscle regeneration toward a goal of improving muscle bulk and strength in the setting of injuries or diseases that cause muscle atrophy.

Extensive evidence has shown that higher levels of some pro-inflammatory cytokines contribute to the development of cachexia. For example, serum tumor necrosis factor  $\alpha$  (TNF $\alpha$ ) and IL-1 $\alpha$  levels are markedly increased in patients with rheumatoid arthritis and cancer. Other cytokines, such as IL-6, IL-1 $\beta$  and proteolysis-inducing factor (PIF) have been reported to contribute to the development of muscle wasting.

Elegant studies show that TNF $\alpha$  binds to its receptor on skeletal muscle resulting in the activation of nuclear factor  $\kappa$ B (NF- $\kappa$ B) mediated by phosphorylation and degradation of the NF- $\kappa$ B inhibitory protein, I $\kappa$ B $\alpha$ . Downstream effects of pathological NF- $\kappa$ B activation in skeletal muscle include the inhibition of new muscle formation and the degeneration of existing muscle. *In vitro* studies support the potential that the I $\kappa$ B $\alpha$  superrepressor (I $\kappa$ BSR), an I $\kappa$ B $\alpha$  genetically engineered to prevent its phosphorylation, can prevent the activation of NF- $\kappa$ B in skeletal muscle and could ameliorate or prevent muscle wasting. Our preliminary studies demonstrate the novel determination of inhibition of activation of NF- $\kappa$ B by cellular FLIP (cFLIP).

Our hypothesis is that the inhibition of the downstream pathways of TNF $\alpha$  causing muscle atrophy and failure of muscle regeneration should be effected intracellularly in muscle fibers. A gene therapy strategy is ideal for the purpose of achieving an ongoing effect that is cell-type restricted. We anticipate that inhibition of NF- $\kappa$ B activation restricted to muscle fibers will provide a therapeutic effect on muscle while avoiding potential toxic effects of inhibiting NF- $\kappa$ B activation in other tissues.

**Body:**

**To characterize an *in vitro* model of cancer-induced muscle wasting in primary muscle cells and in stable muscle cell lines expressing I $\kappa$ BSR or cFLIP.**

We developed a new *in vitro* cell culture assay to study the effects of cancer cell cytokines on muscle cell differentiation and use this assay to test novel gene transfer approaches for the treatment of cancer cachexia. Exposure to conditioned media from selected human cancer cell lines resulted in failure of muscle cell differentiation. A known intracellular mechanism of NF- $\kappa$ B activation as a cause of cancer cachexia was recapitulated in this *in vitro* system. We observed a direct correlation between NF- $\kappa$ B activation and inhibition of myogenic differentiation in the *in vitro* assay. Exposure to inflammatory cytokines and to conditioned media from human cancer cells each resulted in NF- $\kappa$ B activation within primary muscle cells. Failure of myogenic differentiation and the associated activation of NF- $\kappa$ B were prevented by stable expression of either I $\kappa$ BSR or cFLIP, but not by Bcl-xL. These findings were published. As described below, we used the PC-3 cell line to generate a new *in vivo* cancer cachexia model in mice.

Taken together, this study provides an *in vitro* assay that demonstrates secretion of cachexia-inducing factors by certain cancer cell lines that result in the inhibition of myogenic differentiation by activation of NF- $\kappa$ B. Over-expression of cFLIP in muscle cells inhibits both NF- $\kappa$ B-mediated and apoptotic pathways, thereby preventing tumor media-induced inhibition of myogenic differentiation and cytotoxicity. These findings point toward the potential to design novel molecular therapeutics for the treatment of cancer-induced muscle wasting.

**To clone, rescue, and purify adeno-associated viral (AAV) vectors carrying I $\kappa$ BSR or cFLIP.**

We are generating vectors with either ubiquitous or muscle-specific promoter control of expression. AAV serotype 8 vectors provide high levels of muscle transduction and the ability to transduce muscle by systemic delivery. Where possible, we are using self-complementary vectors that result in the highest possible levels of transgene expression.

At our last report, we had rescued the following vectors as high-titer, purified AAV8 vectors: Conventional single strand AAV8 vectors were rescued with the following expression cassettes: CMV-GFP and CMV-cFLIP. Self-complimentary (double strand) AAV8 vectors were rescued with the following expression cassettes: CMV-I $\kappa$ BSR and MCK-GFP. The double strand MCK-GFP vector has been tested by direct intramuscular injection showing high levels of transgene expression.

Since the last report, we rescued the MCK-I $\kappa$ BSR double strand vector as AAV8. The MCK-cFLIP double strand vector plasmid was difficult to clone, but we finally achieved it. We are currently rescuing that plasmid as AAV8. We observed widespread skeletal muscle expression from the MCK-GFP AAV8 vector after systemic delivery. We also observed skeletal muscle expression after intramuscular and systemic delivery of the MCK-I $\kappa$ BSR AAV8 vector.

**Characterization of a new PC-3 cell cancer cachexia model in mice.**

We have refined our model of muscle cachexia in mice in order to test molecular therapeutics *in vivo*. We generated a novel model of cancer cachexia induced by PC-3 cells and compared it to an established model induced by MCA-26 cells. We reported initial findings on the *in vivo* PC-3 cell cancer cachexia model in our last report. We have now completed those studies and prepared a manuscript for submission. We showed that tibialis anterior and quadriceps muscles had increased activation of NF- $\kappa$ B in the PC-3 cell model of cancer cachexia, as predicted from our *in vitro* studies exposing muscle cells in culture to supernatant from PC-3 cells. Interestingly, the gastrocnemius, which did not show an increase in activated NF- $\kappa$ B, instead showed increased levels of phosphorylated eukaryotic initiation factor 2 alpha (p-eIF2- $\alpha$ ) indicating decreased protein synthesis contributing to the cachexia phenotype. This raises the interesting possibility that increased protein degradation or decreased protein synthesis may contribute to cachexia to different degrees in different muscle groups.

**To apply AAV8 vector strategies to ameliorate cancer cachexia.**

Five-week old CD2F1 mice received intramuscular administration of either AAV8-MCK-dsI $\kappa$ BSR or AAV8-CMV-dsI $\kappa$ BSR or AAV8-CMV-ss cFLIP vector 1 week prior to MCA-26 tumor inoculation. Body weight and tumor growth were monitored every other day. All mice developed tumors and cachexia beginning at about 12 days after tumor inoculation (Figure 1). Three weeks tumor after inoculation the mice were sacrificed and hind-limb muscles were dissected, weighed, and snap-frozen for analysis. The tibialis anterior muscle injected with AAV8-MCK-dsI $\kappa$ BSR showed a significant increase in weight compared to tumor-bearing control (Figure 2). Tibialis anterior muscle injected with each of the 3 therapeutic AAV8 vectors showed a significant increase in muscle fiber diameters compared to tumor-bearing control (Figure 3).

Our results suggest that vectors expressing proteins with the intended effect of decreasing NF- $\kappa$ B activation can ameliorate cancer cachexia *in vivo*. Future studies are needed to test vector-mediated gene delivery of I $\kappa$ BSR and cFLIP by systemic delivery in cancer cachexia models.

Figure 1A

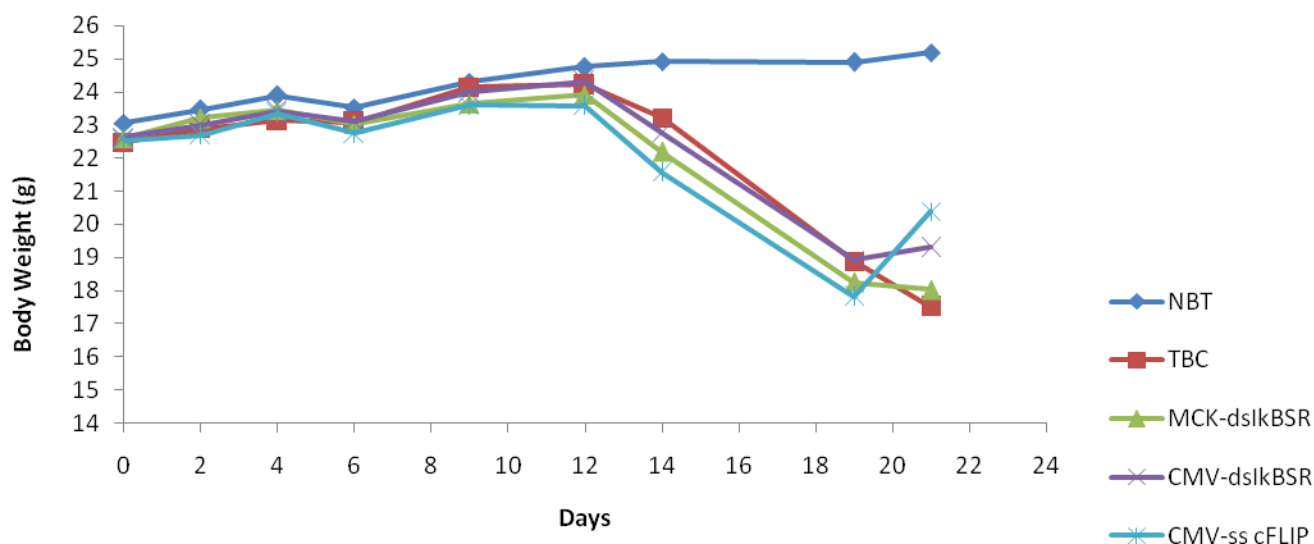
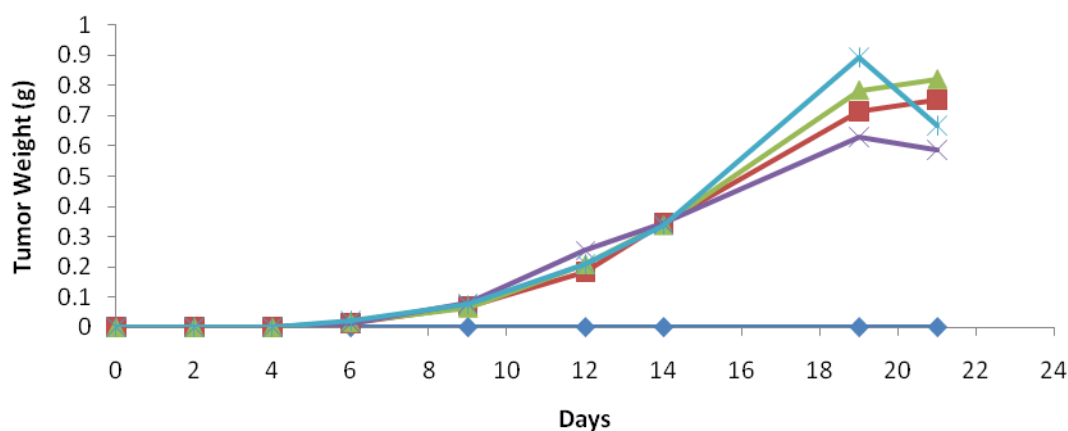


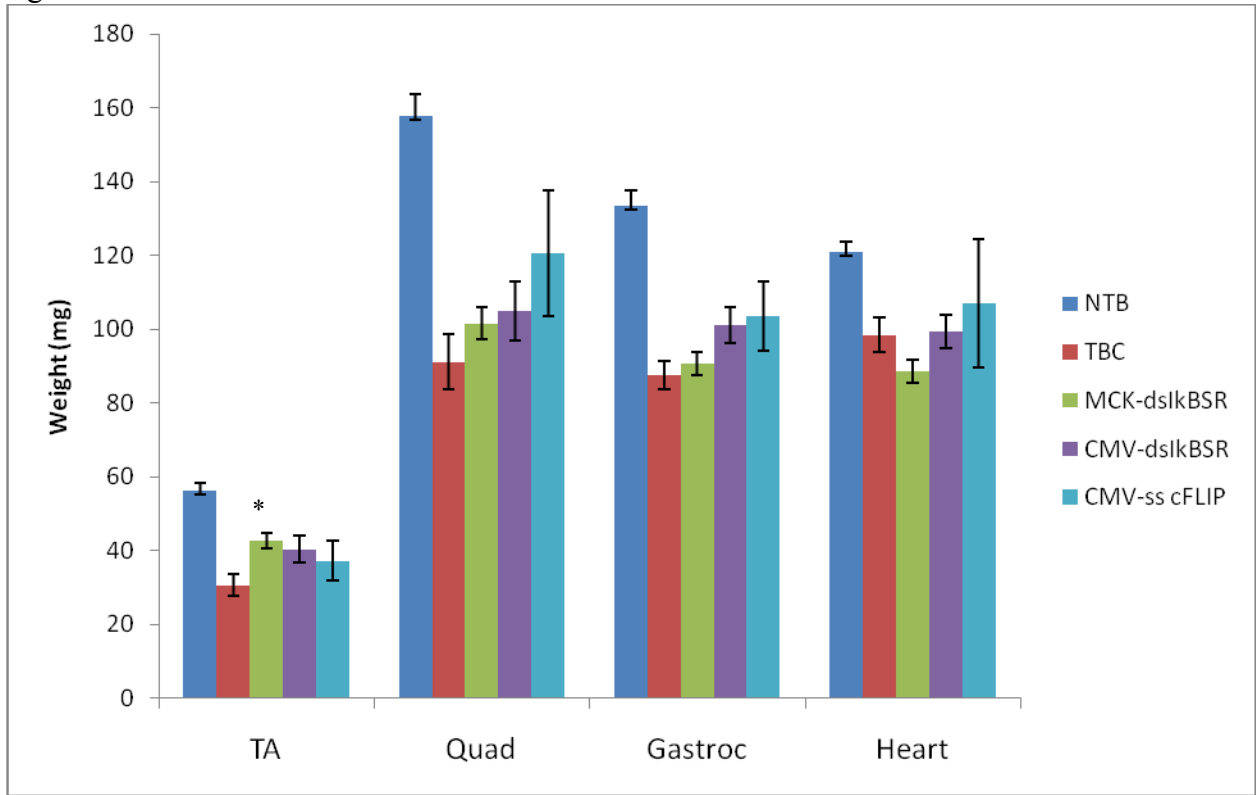
Figure 1B



**Figure 1. Effect of intramuscular administration of AAV8 carrying MCK-I $\square$ BSR or CMV-I $\square$ BSR or CMV-cFLIP on body and tumor weight of MCA-26 tumor-bearing in comparison with non-tumor-bearing control (NTB)**

CD2F1 mice were intramuscularly injected with AAV8 vector carrying MCK-I $\square$ BSR or CMV-I $\square$ BSR or CMV-cFLIP on tibialis anterior and quadriceps muscle ( $3.4 \times 10^{10}$  v.p./muscle) and one week after the mice received MCA-26 tumor inoculation ( $10^6$  cells/mouse) (day 0). (A) Body weight change of mice bearing MCA-26 tumor with or without AAV8 treatment as compared to NTB. (B) Tumor growth rate in MCA-26 tumor-bearing mice with or without AAV8 treatment. The number of mice in each group n=5.

Figure 2



**Figure 2. Treatment with AAV8 carrying MCK-I $\square$ BSR or CMV-I $\square$ BSR or CMV-cFLIP results in improved muscle weight in mice bearing MCA-26 tumor**

Mice were sacrificed and hind-limb muscles (TA = tibialis anterior, Quad = quadriceps, Gastroc = gastrocnemius) and heart were collected. The average weight of each individual muscle of NTB and MCA-26 tumor-bearing mice with or without AAV8 treatment are shown. Differences from tumor-bearing without AAV8 treatment (TBC = tumor-bearing control) are shown \* =  $p < 0.05$ .

Figure 3A

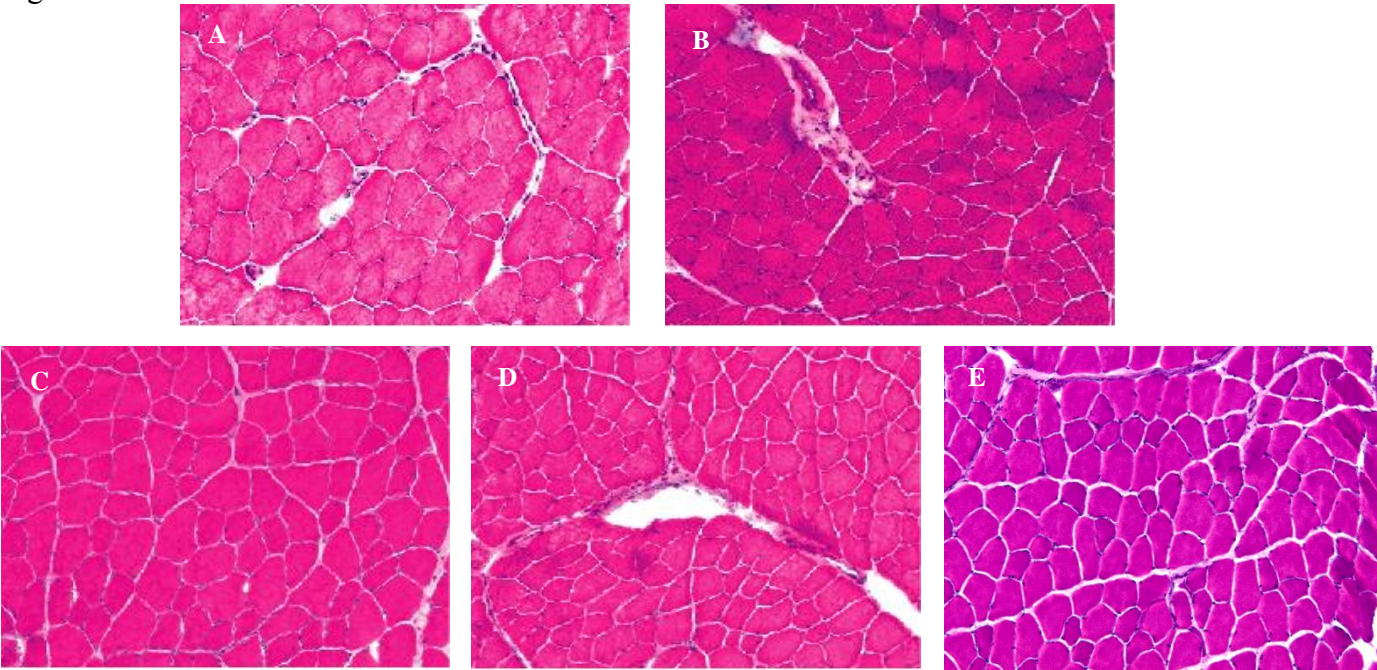
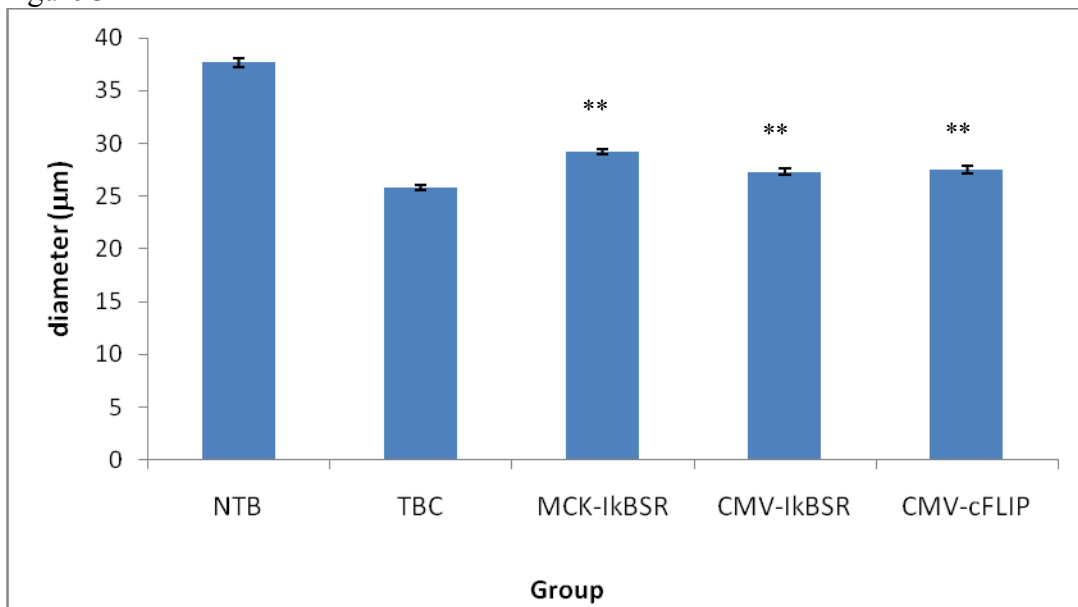


Figure 3B



**Figure 3. Treatment with AAV8 carrying MCK-IκBSR or CMV-IκBSR or CMV-cFLIP results in increased muscle fiber diameters in mice bearing MCA-26 tumor**

Representative H&E staining of TA muscle section is shown in (A); (a) non-tumor-bearing control, (b) MCA-26 tumor-bearing control, (c) AAV8-MCK-IκBSR injected MCA-26 cachexia, (d) AAV8-CMV-IκBSR injected MCA-26 cachexia, (e) AAV8-CMV-cFLIP injected MCA-26 cachexia. The average muscle fiber diameter of each group is shown in (B). Differences from TBC (tumor-bearing control) are shown \*\* =  $p < 0.01$ .

#### Key Research Accomplishments:

- Development of an *in vitro* assay of muscle wasting induced by cancer cytokines
- Demonstration of importance of NF-κB activation as a molecular mechanism for cancer-induced muscle wasting in the *in vitro* assay
- Use of the *in vitro* assay to identify cFLIP as a novel potential therapeutic agent for the treatment of cancer-induced muscle wasting
- Generation of single strand and double strand AAV8 vectors
  - Single strand AAV8 vectors
    - CMV-GFP
    - CMV-cFLIP
  - Double strand AAV8 vectors
    - MCK-GFP
    - CMV-IκBSR
    - MCK-IκBSR
  - Cloned as plasmid
    - AAV-MCK-D(+)-c-FLIP
- Refinement of 2 cancer cachexia models in mice
- Testing of AAV8 vectors carrying IκBSR and cFLIP for amelioration of cancer cachexia in an *in vivo* murine model

Investigator: Johnny Huard

**Reportable Outcomes:**

Jiang Z, Clemens PR. Cellular caspase-8-like inhibitory protein (cFLIP) prevents inhibition of muscle cell differentiation induced by cancer cells. FASEB J 2006 Dec;20:E1979-E1989.

Sae-Chew P, Clemens PR. A Novel Muscle-Wasting Mouse Model Induced By Human Prostate Cancer Cells: Comparison with a Well Established Model Induced By Murine Colon Adenocarcinoma Cells. Prepared for submission (attached).

**Conclusions:**

Our studies to date identify an *in vitro* assay that allows us to test molecular therapies that have the potential to treat muscle wasting induced by cancer. We anticipate that these results can be generalized to the treatment of other genetic and acquired causes of muscle wasting. We produced multiple AAV8 vectors with expression cassettes designed to inhibit activation of NF- $\kappa$ B and ameliorate cancer cachexia. We applied several newly developed AAV8 vectors for treatment of cancer cachexia in a murine model.



## Vector Core (Bing Wang)

### Final report:

Vector Core of the DOD project (W81XWH-06-1-0406)

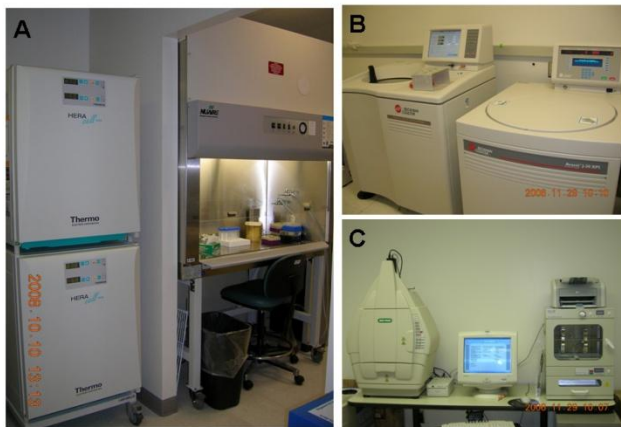
Sub-title: The structure, production and purification of adeno-associated viral, adenoviral and retroviral vectors

### Introduction:

The Vector Core continues to engineer, and produce high quality viral vectors which have been utilized in many of the projects outlined above. Briefly, the Molecular Therapy Laboratory (MTL) in the Department of Orthopaedic Surgery is focusing on viral based gene transfer and stem cell technologies for musculoskeletal diseases, mainly by using recombinant adeno-associated viral (rAAV), retro-viral and lenti-viral vectors which represent the most promising approaches to aid in the repair and regeneration of muscle, bone, ligament, tendon, and joint capsules. In the meanwhile, MTL also serves as a Vector Core of a DOD project (W81XWH-06-1-0406, PI: Dr. Johnny Huard) for the design, construction and production of a lots of viral vectors which are used to gene transfer and genetic engineering of stem cells in the whole project.

The Vector Core is located in the Biomedical Science Tower, room E1603. Total dedicated Vector Core space is approximately 500 square feet for molecular biology and viral vector production. Inventory of major equipment includes one tissue culture hood and one temperature-controlled CO2 incubator for cell culture and viral vectors production (**Figure 1 A**). In addition, Vector Core is also equipped with one Beckman TM L-100 XP Ultracentrifuge, one Beckman Avanti TM J-20 XP high-speed centrifuge for the purification of plasmid DNA and viral vectors (**Figure 1B**). Moreover, one Beckman refrigerated table-top centrifuge, two microfuges, one refrigerator, one BioRad PCR machine, one UV spectrophotometer, and one BioRad gel documentation camera (**Figure 1C**), and two BioRad electric gel transfer apparatuses will be used for molecular analysis and

vectors construction. Also, one Nikon inverted fluorescent microscope and -30°C and -80°C freezers, and one liquid nitrogen tank are established for evaluating the expression of report genes, storages of plasmid DNA, viruses and cell clones.



**Figure 1.** Major Equipment

### Body

#### Development and production of AAV vectors

The Vector Core is actively engaged in multiple applications of rAAV vectors for gene therapy, including different serotypes of AAV vectors, both single and self-complementary AAV vectors, inducible vector system. Moreover, we developed the different promoters in AAV vectors and gene-silencing AAV vectors. As a vector core, we collaborated with many laboratories internal and

external the University of Pittsburgh. Our goal is to develop very useful viral vectors for directly gene transfer and to aid in the characterization of the cells, track the cells and genetically modify the cells to express beneficial proteins to enhance their transplantation efficiency. Such as Decorin, mini-dystrophin, and myostatin propeptide genes etc. were constructed in AAV vectors. As described in following, we produced lots of AAV vector for the aims in this project:

1. AAV2-D(+)-CMV-eGFP
2. AAV6-D(+)-CMV-eGFP
3. AAV8-D(+)-CMV-eGFP

4. AAV9-D(+)-CMV-eGFP
5. AAV8-D(+)-CMV-eGFP
6. AAV8-D(+)-tMCK-eGFP
7. AAV2-D(+)-CB-eGFP
8. AAV2-1060-hrGFP
9. AAV2-1070-hrGFP
10. AAV2-1060-Gluciferase
11. AAV2-1070-GLuciferase
12. AAV2-CMV-sflt1
13. AAV2-D(+)-BMP2-spA
14. AAV2-D(+)-BMP2-SV40
15. AAV2-D(+)-CMV-TGF $\beta$ 1
16. AAV2-CMV-minidystrophin (3858)
17. AAV2-dMCK-minidystrophin (3858)
18. AAV6-D(+)-CMV-BMP4
19. AAV2-D(+)-CMV-VEGF
20. AAV1-CMV-Decorin

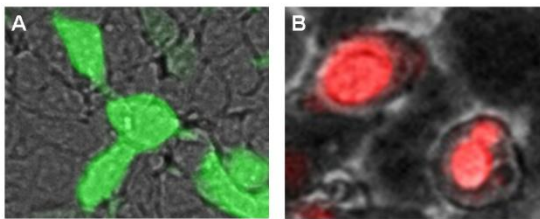
#### Development and production of lenti-viral vectors

In the meanwhile, we also updated the BSL-2 to BSL-2+ for development of lenti-viral vectors using in the aims of this project, including green (GFP) and red (RFPN) reporter genes and silencing lenti-viral vectors targeting to human and mouse VEGF genes.

1. lenti-CMV-GFP
2. lenti-CMV-RFPN
3. lenti-CMV-Luciferase
4. lenti-minidytrophin (3849)-GFP
5. lenti-shRNA-mouse VEGF-GFP
6. lenti-shRNA-human VEGF-GFP

#### Efficiency of viral vectors

To test the efficiencies of AAV and lenti-viral vectors, we made different viral vectors and the sequential dosages of reporter viral vectors to test which viral vectors could achieve the higher transduction efficiency and



**Figure 3.** Transduction of AAV- and lenti-viral vectors in 293 cultured cells 36 hours post-infection. (A) shows AAV-GFP, and (B) represents Lenti-RFP-N

lower dose vector loading, such as green fluorescent protein (GFP) and red fluorescent protein in nucleolus (RFP-N), as shown in **Figure 3**. Also, we used same strategy to optimize the serotype of AAV vector that appears a variety of AAV transduction in the different cells and tissues. The advantage of the GFP or RFP reporter is that it can be directly visualized on the whole limb as well as on the cryo-sections. Its fluorescent intensity could also be quantitated by the Nikon microscope imaging software we have been using in the lab. Usually, at 3 weeks following implantation, at which time the GFP gene expression is expected to reach a considerable level for

detection and quantitation, the animals would be sacrificed and skeletal muscles, hearts and liver will be collected for photographs for GFP or RFP expression and for microscopic photographs and quantitations from the intensity of the fluorescence after cryo-thin-section.

To achieve *ex vivo* gene transfer into *mdx* skeletal muscle using lenti-minidystrophin gene, we constructed a fusion protein containing minidystrophin and GFP reporter gene. GFP reporter can monitor the proliferation and differentiation of muscle derived stem cells *in vivo*, and it can also represent the expression of minidystrophin gene directly under microscopy, without toxicity and immune response. In preprimary study, we created this fusion protein construct in a pEGFP-N1 plasmid, and then cloned it into lenti-viral vector under the control of the CMV promoter. As shown in **Figure 4**, the fusion protein was expressed in both C2C12 and 293 cells after transfection.

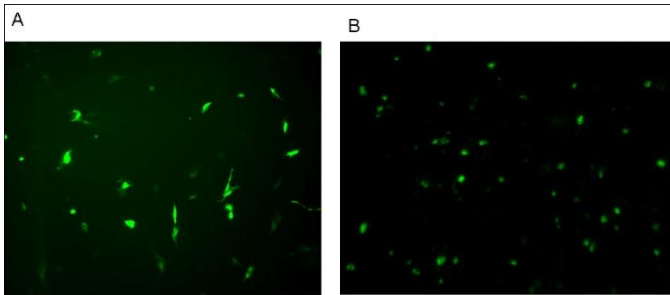


Figure 4. The expression of mini-dystrophin-GFP fusion protein after transfection. (A) 24 hours post-transfection of Mini-dystrophin-GFP fusion in C2C12 by Biotex. (B) 4 days post-transfection of Lenti-Mini-dystrophin-GFP fusion in 293 cells.

### Achievements

Invited review book –Regenerative therapy for the musculoskeletal system using recombinant adeno-associated viral vectors”

1. **Bing Wang** and Johnny Huard, 2008, the Chapter –Gene therapy for the treatment of muscle disorders”
2. **Bing Wang** and Freddie H. Fu, 2008, the Chapter –AAV vectors for soft tissue reconstruction”

### Publication and abstracts in 2008 and 2009

1. Chunping Qiao et al. *Human Gen Therapy*, 2008, 19 (3), 241-253.
2. Bing Wang et al. *Gene Therapy*, 2008, 15 (15), 1099-1106.
3. Bing Wang et al. *Gene Therapy*, 2008, 15 (22), 1489-1499, correspondence author.
4. Juan Li et al. *Hum Gene Ther*. 2008, 19:958-964.
5. Bing Wang et al. *Journal of Orthopaedic Research*, 2009,27:421-426, correspondence author.
6. Bin Li et al. *Journal of Biomechanics*, 2008, 41:3349-3353.
7. Michael Y. Mi et al. *Molecular Therapy*, 2008, vol.16, suppl 1, S103, correspondence author.
8. Peiqi Hu et al. *Molecular Therapy*, 2008, vol.16, suppl 1, S201
9. Bhanu M et al. *Molecular Therapy*, 2008, vol.16, suppl 1, S293
10. Joseph Kornegay et al. *Molecular Therapy*, 2008, vol.16, suppl 1, S374
11. Ying Tang; Bin Li, James H-C Wang, Johnny Huard, Melessa Salay, Bing Wang. *In vitro* AAV-mediated gene transfer in human fibroblasts. 54<sup>th</sup> Annual Meeting of Orthopaedic Research Society, March 1<sup>st</sup> – March 6<sup>th</sup>, 2008
12. Bin Li, Micheal Lin, Ying Tang, Bing Wang, James H-C Wang. Micropatterned C2C12 cells exhibit enhanced differentiation into myotubes – a novel study using cell traction force microscopy. 54<sup>th</sup> Annual Meeting of Orthopaedic Research Society, March 1<sup>st</sup> – March 6<sup>th</sup>, 2008
13. Guangheng Li, Bo Zheng, Andres J. Quintero, Arvydas Usas, Bing Wang, Laura B. Meszaros, Karin A. Corsi, Johnny Huard. Therapeutic Utility of Heterotopic Ossification Induced by AAV-BMP4 in Skeletal Muscle. 54<sup>th</sup> Annual Meeting of Orthopaedic Research Society, March 1<sup>st</sup> – March 6<sup>th</sup>, 2008
14. Mi, Y.M; Tang, Y; Li, G-H; Salay, M.N; Niyibizi, C; Huard, J; Wang, B. AAV Based *Ex Vivo* Gene Therapy in Rabbit Adipose Stem/Progenitor Cells for Osteogenesis. 55<sup>th</sup> Annual Meeting of Orthopaedic Research Society, February 22 – 25, 2009, Las Vegas, Nevada.
15. Tang, Y; Reay, D.P; Salay, M.N; Mi, Y.M; Clemens, P.R; Guttridge, D.C; Robbins, P.D.; Huard, J; Wang, B. Delivery of Dominant Negative IKKs by Recombinant Adeno-associated Virus: Efficient Improvement in Muscle Regeneration in *mdx* Mice. 55<sup>th</sup> Annual Meeting of Orthopaedic Research Society, February 22 – 25, 2009, Las Vegas, Nevada.

16. Michael Y. Mi, Ying Tang, Melisa N. Salay, Guangheng Li, Johnny Huard, Freddie H. Fu, Christopher Niyibizi and Bing Wang. *AAV ex vivo Gene Therapy for Osteogenesis and Chondrogenesis. Submitted to 12<sup>th</sup> Annual meeting of ASGT (May 27-30, 2009, San Diego, California).*
17. Daibang Nie, Dong Wei, Michael Y. Mi, Ying Tang, Allan Z. Zhao, Yifan Dai, Johnny Huard, and Bing Wang. Muscle Specific Gene Transfer of the PEPCK-C Improves Physical Activity in Mice. *Submitted to 12<sup>th</sup> Annual meeting of ASGT (May 27-30, 2009, San Diego, California).*
18. Ying Tang, Daniel P. Reay, Melessa N. Salay, Michael Y. Mi, Paula R. Clemens, Denis C. Guttridge, Paul D. Robbins, Johnny Huard, Bing Wang. AAV Based Blocking of NF-kappa B Pathway Improves Muscle Regeneration in *mdx* Mice. *Submitted to 12<sup>th</sup> Annual meeting of ASGT (May 27-30, 2009, San Diego, California).*

#### Awards

1. Ying Tang et al. *In vitro* AAV-mediated gene transfer in human fibroblasts. Oral presentation given at the 54<sup>th</sup> Annual Meeting of Orthopaedic Research Society, March 1<sup>st</sup> – March 6<sup>th</sup>, 2008.
2. Michael Y. Mi et al. AAV Based *Ex Vivo* Gene Therapy in Rabbit Adipose Stem/Progenitor Cells for Osteogenesis” was accepted as a podium presentation at the 55<sup>th</sup> Annual Meeting of Orthopaedic Research Society, February 22 – 25, 2009, Las Vegas, Nevada.

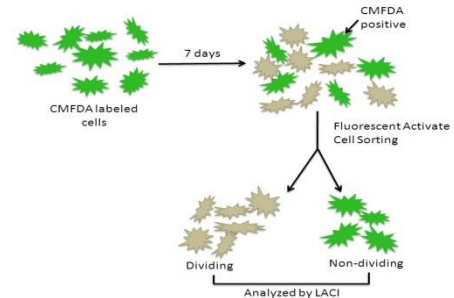
#### **Conclusion**

The Vector Core for this project provided a series of viral vectors containing reporter and therapeutic genes proposed in aims. Also, it will develop the Tet-On retro-viral vector system to express a VEGF-LacZ fusion protein.

## Bioreactor Core Progress Report March 2011 (Johnny Huard and Bridget Deasy)

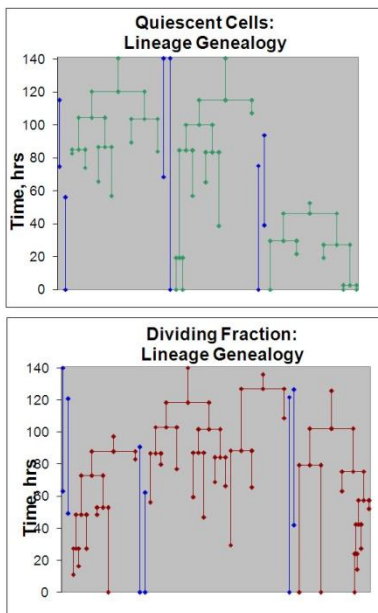
In 2010, the Bioreactor Core continues to offer unique technology to members of the stem cell research community at the University of Pittsburgh. Here we include another example of how this technology is being used to understand stem cells is below. The project is title, “Methods to identify and Isolate Potent Human Muscle Derived Stem Cells”, TA Bissell, SM Chirieleison and BM Deasy. Following this example, we include a list of publications and abstracts that have used this technology. We also list awards associated with the use of this technology.

The objective of the project “Methods to identify and Isolate Potent Human Muscle Derived Stem Cells” is to investigate the presence of quiescent cells in muscle derived stem cells (MDSCs) by using live cell imaging. Using FACs and LACI we 1.) directly identified quiescent cells and 2.) isolated the quiescent subpopulation and 3.) verified that the quiescent subpopulation re-activates/ re-enters the cells cycle to give rise to new progeny. Stem cell biology requires an understanding of stem cell population heterogeneity so that the stem cells can be used effectively for regenerative medicine. Stem cell populations contain dividing and non-dividing subpopulations. Among the non-dividing fraction are quiescent cells, for which no definitive markers exists, are cells that are not currently dividing, but have the potential to actively start proliferating. Because of their ability to actively proliferate and give rise to multipotent progeny, the quiescent cells may be the most effect subpopulation for regenerative medicine. Retrospective analysis of previous studies has shown that muscle stem cell populations that contained a larger percentage of quiescent cells contributed to more muscle regeneration (1-3). Further, during stem cells transplantation studies, it has been found that only a small fraction of cells that survive the transplantation process and contribute to regeneration. Live automated cell imaging (LACI) allows human muscle derived stem cells to be observed in a controlled environment for extended periods of time. LACI is a useful tool to classify the subpopulations because it allows the cells to be tracked to determine divisional status and hierarchical lineage. Through the construction of cell lineages and parameters using LACI, the quiescent subpopulation can be identified and studied for its role in cell therapeutics.



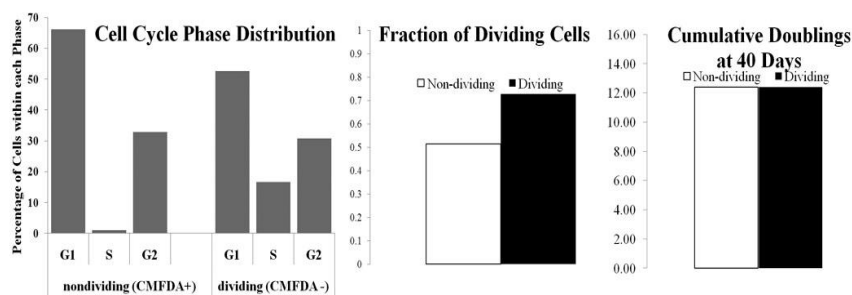
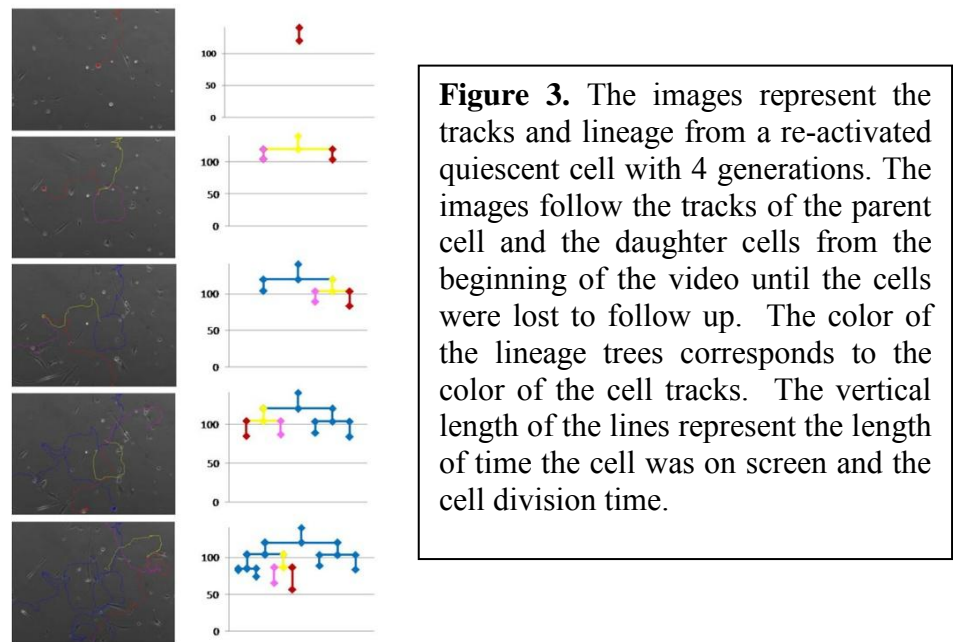
The cells were labeled with a fluorescent cytoplasmic dye, 5-chloromethylfluorescein diacetate (CMFDA). CMFDA decreases in concentration and intensity after a cell divides because the signal is split between the daughter cells. After the cells were in culture for five days, flow cytometry was used to separate the cells into CMFDA positive (non-dividing) and CMFDA negative (dividing) subpopulations. PI cell cycle analysis was performed on the parent population (Figure 1).

The images were analyzed for behavioral parameters and cell lineages.. Cell were tracked and divisions were recorded in order to determine cell histories and to construct lineage trees. Cell division time, population doubling time and mitotic fraction was determined using the images. (Figure 2-4).



**Figure 2.** Representative lineage trees from the non-dividing, CMFDA positive subpopulation (A) and trees from the dividing, CMFDA negative subpopulation (B). Blue lines represent non-dividing cells, which were on screen for over 40 hours (twice the average DT). The green lines represent quiescent cells that have become activated and begun to divide, and red lineage trees show division for up to five generations





**Figure 4.** PI cell cycle analysis showed more non-dividing cells in G1 phase. The dividing cell population had a higher percent of dividing cells. In the non-dividing population, 61% of the cells did not divide until after 4 days. 50% of the dividing cells began dividing within the first 6 hrs. In a in-vitro expansion, both populations had 12.4 doublings after 40 days.

In sum, this study showed (1) Labeling the cells with CMFDA and sorting the cells with flow cytometry allows for the quiescent subpopulation to be isolated and identified. (2) Live cell imaging allowed the isolation of the quiescent subpopulation to be validated. The quiescent subpopulation took longer time then the dividing population to begin dividing. (3) The quiescent cells did re-activate and enter the cell cycle. Cell lineages with four generations were observed. The in-vitro expansion showed that the subpopulations had the same longevity.

The ability to isolate and identify the subpopulations allows for a more in depth understanding of stem cell heterogeneity. Regenerative medicine techniques require using cells that can survive the transplantation process and contribute to regeneration. These methods allow the younger quiescent subpopulation to be studied, and provides a method of examining the relationship between cell therapies and tissue repair.

**Key Core Users and Collaborative Projects (a sample of several core collaborations)**

1. Dr. Bridget Deasy, Department of Orthopedic Surgery, University of Pittsburgh Medical Center
2. Dr. Johnny Huard, Department of Orthopedic Surgery, University of Pittsburgh Medical Center
3. Dr. Yong Li, Department of Orthopedic Surgery, University of Pittsburgh Medical Center
4. Dr. Fabrisia Ambrosio Department of Rehabilitation Sciences, University of Pittsburgh Medical Center
5. Dr. Nam Vo. Dept of orthopedic Surgery, University of Pittsburgh

**2010-2011 JOURNAL and ABSTRACT PUBLICATIONS which include Bioreactor Core Technology**

**JOURNAL PUBLICATIONS**

- A. Chirieleison, SM, Scelfo, CC, Bissell, TA, Anderson, JE, Koebler, D, Yong Li, Deasy, BM. Robotic imaging systems for biological study of dynamic cell behavior., 2010 *ACCEPTED Biotechnology Progress*.
- B. **Deasy, BM\*, Chirieleison SM, Witt, AM, Peyton, MJ, Bissell, TA.** 2010. Tracking stem cell function with computers via live cell imaging: Identifying donor variability in human stem cells. *Operative Techniques in Orthopedics*. 20 (2):127-135. \*corresponding author.
- C. Tea Soon Park, Manuela Gavina, Chien-Wen Chen, Bin Sun, Pang-Ning Teng, Johnny Huard, Bridget M Deasy, Ludovic Zimmerlin, Bruno Peault. Placental Perivascular Cells for Human Muscle Regeneration. *Stem Cells and Development*. doi:10.1089/scd.2010.0354.
- D. Leloup L, Shao H, Bae YH, Deasy B, Stolz D, Roy P, Wells A. m-Calpain activation is regulated by its membrane localization and by its binding to phosphatidylinositol 4,5-bisphosphate. *J. Biol. Chem.* 2010 285: 33549-33566.
- E. **Chirieleison SM** , Feduska JM, Schugar RC, Sanford SL, Scelfo CC, Askew Y, Deasy BM. 2010. Human Muscle-Derived Cells Isolated by Differential Adhesion Rates Exhibit Differences in Phenotype and Contribution to Skeletal Muscle Regeneration in mdx/SCID model. *Accepted Tissue Engineering*.
- F. **Urish, KL, Deasy BM, Huard J.** (2011). Automated Segmentation, Classification, and Visualization of Fluorescent Time-lapsed Microscopy Images. In submission.

**ABSTRACT PUBLICATIONS (selected list of > 30)**

1. Witt, A M; Nance, J J; James, S D; Usas, A; Deasy, B M. Human Donor Variability in Osteogenesis is a Consideration in the Therapeutic Use of Umbilical Cord. 2010. International Society for Stem Cell Research; San Francisco, CA .
2. Deasy, BM, Bissell, TA, Chirieleison, SM, Piganelli JD. Ex Vivo Expanded Human Muscle Stem Cells show increased levels of reactive oxygen species and increased sensitivity to oxidative stress. The Ottawa Conference on New Directions in Biology and Disease of Skeletal Muscle 2010.
3. Deasy, BM, Feduska JM, Payne TR, Li Y, Ambrosio F, Huard J. Improved muscle repair through transplantation of VEGF-expressing muscle stem cells in mdx skeletal muscle. Ottawa Meeting. The Ottawa Conference on New Directions in Biology and Disease of Skeletal Muscle 2010.
4. Deasy, BM, Chirieleison SM; Witt, AM; Bissell, TA; Peyton, MJ. 2010. Tracking stem cell activity with computers via live cell imaging: Identifying donor variability in human umbilical cord stem cells. *Pittsburgh Orthopedic Journal*
5. Bissell, T A; Chirieleison SM; Witt, M; Kline, D E; Deasy, B M. 2010. Identification of Potent Human Muscle Stem Cells by Live Cell Imaging. *Pittsburgh Orthopedic Journal*
6. Jordan E. Anderson, Steven M. Chirieleison, Christopher C. Scelfo, Taylor A. Bissell, Yong Li , Doug J. Bridget M. Deasy 2010. Robotic imaging systems for biological study of dynamic cell behavior in cell migration assays. *Pittsburgh Orthopedic Journal*

7. Anderson JE, Yao V, Chu CR, Deasy B. 2010. THE USE OF TIME-LAPSED MICROSCOPY TO STUDY CELL MIGRATION AND CHEMOATTRACTION. *Pittsburgh Orthopedic Journal*
8. Chirieleison S C; Nance, JJ; Schugar, RC; Witt, AM; Deasy, B M. 2010. Sex Differences in In Vivo Skeletal Muscle Regeneration after Transplantation of Human Umbilical Cord Stem Cells to mdx/SCID mice. *Pittsburgh Orthopedic Journal*
9. Nance, JJ; Wescoe, KE; Witt, AM; Deasy, B M. 2010. Induction of Chondrogenesis in Human Umbilical Cord Derived Stem Cells in a Hypoxic Environment. *Pittsburgh Orthopedic Journal*
10. Witt, AM Nance, JJ; James, SD; Wescoe, KE; Usas, A; Deasy, B M. 2010. Human Donor Variability in Osteogenesis of Human Umbilical Cord Stem Cells. *Pittsburgh Orthopedic Journal*
11. Friesmuth, KR Payne, KA; Schugar, RC, Chu, CR; Deasy, B M Comparison of Expandability of Mesenchymal Cells from Newborn Umbilical Cord and Adult Bone Marrow. *Pittsburgh Orthopedic Journal*
12. Nance, J J; Wescoe, K E; Witt, A M; Deasy, B M Induction of Chondrogenesis in Umbilical Cord Derived Stem Cells in Hypoxic Environment. 2010 Orthopaedic Research Society; New Orleans, LA
13. Bissell, T A; Chirieleison S C; Witt, M; Kilne, D; Deasy, B M. Potent Human Muscle Stem Cells are Identified by Live Cell Imaging. 2010 Orthopaedic Research Society; New Orleans, LA
14. Chirieleison, S M; Nance, J J; Schugar, R.C. Witt, A.M. Deasy, B M Sex Differences in In Vivo Skeletal Muscle Regeneration after Transplantation of Human Umbilical Cord Stem Cells to mdx/SCID mice. 2010 Orthopaedic Research Society; New Orleans, LA

### **AWARDS and OTHER ACCOMPLISHMENTS**

1. **A new NIH award** STTR 1R41AR057629-01 "Processing and Preservation of Human Umbilical Cord Stem Cells for Cell Therapeutics" to BM Deasy was received and is based in part on the live cell imaging technology to facilitate the identification of stem cells processing standards.
2. Two University of Pittsburgh Bioengineering undergraduate student were awarded fellowships related to their projects which use live cell imaging:
  1. **Jordan E. Anderson**- Honors Research Assistantship, University of Pittsburgh. Mentor: Dr. BM Deasy
  2. **Taylor A. Bissell** - Chancellor's Undergraduate Research Fellowship Univ of Pittsburgh. Mentor: Dr. BM Deasy
3. The LiveCell Imaging Lab technology was featured at the annual Orthopedic Research Society Meeting in 2011 at a special **Spotlight on Research** workshop.



**Micro-CT Core Progress Report March 2011**  
**(Johnny Huard and Arvydas Usas)**

We continue to use the vivaCT 40 (Scanco Medical) imaging system for nondestructive 2-D and 3-D visualization and quantitative analysis of mineralized matrix volume, density and other structural parameters of bone tissue. VivaCT 40 system enables us to perform live animal imaging on the same animal at different time points; therefore we are able to reduce the number of experimental animals and cut the cost for animal housing and care. We are also performing CT imaging of various animal body parts and tissues (calvaria, spine, extremities, muscles, etc.) harvested after animal euthanasia and stored in fixative solution for extended period of time.

We are using continuous cell pellet culture imaging to detect matrix mineralization after osteogenic stimulation in vitro. This system we believe can be very useful for the screening of cellular candidates for bone tissue engineering.

We began new studies where we use microCT for evaluation of bone in various animal models of accelerated aging (dkO mice, *Ercc1*-deficient mice, and *Zampste24* metalloproteinase-deficient mice). We will evaluate various parameters of bone structure in these animals. We will also create calvarial and long bone defect in these mice and evaluate bone healing. After this we will inject muscle-derived stem cells in aged animals in order to improve bone formation and enhance bone healing. We are planning to initiate microCT for cartilage imaging using various contrast agents.

During the report period the use of micro-CT contributed to the following research accomplishments by the members of our laboratory:

1. MDSCs promote bone healing by contributing directly to bone regeneration and by inducing early and enhanced inflammation and angiogenesis. Gao X, et al. NIRA poster presentation at the ORS meeting 2011, Long Beach, CA.
2. Repair of Non-Healing Bone Defect by Muscle-Derived Stem Cells. Podium presentation at the ORS meeting 2011, Long Beach, CA.
3. Effect of Sex Hormones on Bone Defect Repair by Muscle-Derived Stem Cells. Poster presentation at the ORS meeting 2011, Long Beach, CA.
4. Dynamic observation revealed muscle derived stem cells transplanted in the cranial skull defect induce early inflammatory response and angiogenesis to promote bone healing. Gao X, et al. Poster presentation at the ORS meeting 2011, Long Beach, CA.
5. The Influence of Platelet-Rich Plasma on In-vitro Proliferation, Osteogenic, Chondrogenic, and Myogenic Differentiation of Human Muscle Derived Progenitor Cells. Li H, et al. Poster presentation at the ORS meeting 2011, Long Beach, CA.
6. Alkaline Phosphatase Expressing Human Skeletal Muscle-Derived Cells Exhibit Distinct Osteogenic Differentiation Potential In Vitro and In Vivo. Usas A, et al. Poster presentation at the ORS meeting 2011, Long Beach, CA.
7. Pericyte-based human tissue engineered vascular grafts. He W, et al. Biomaterials. 2010 Nov;31(32):8235-44.
8. Accelerated aging of intervertebral discs in a mouse model of progeria. Vo N, et al. J Orthop Res. 2010 Dec;28(12):1600-7.
9. Role of PI3K, ERK1/2, and p38 MAPK pathways in BMP4-induced matrix mineralization by MDSCs. Payne-Corsi K, et al. Manuscript accepted for publication in Tissue Eng.
10. Inhibition of NF- $\kappa$ B delays the onset of age-related degenerative diseases. Tilstra JS, et al. Manuscript in preparation for submission.

11. Isolation and characterization of human ACL-derived vascular stem cells. Matsumoto T, et al. Manuscript submitted to Cell Transplantation.
12. Myoendothelial cells: a novel stem cell population from adult human skeletal muscle. Zheng B, et al. Manuscript submitted to Journal of Molecular Cell Biology.
13. Identification and characterization of chondrogenic progenitor cells in adult skeletal muscle. Li GH, et al. Manuscript submitted to Journal of Molecular Cell Biology.
14. Osteogenic potential of male and female human skeletal muscle derived cells. Corsi-Payne K, et al. Manuscript in preparation.
15. Human skeletal muscle cells can undergo matrix mineralization in vitro and facilitate bone repair after delivery on SIS scaffold. Usas A, et al. Manuscript in preparation.
16. The donor-host cell interaction in muscle stem cell based bone regeneration. Gao X, et al. Manuscript in preparation.

Following is the list of current research projects that involve the use of micro-CT core:

1. Osteogenic potential of different populations of human muscle-derived cells, sorted by FACS for high and low ALP, ALDH expression, before and after transduction with BMP4 (NIH funded project).
2. Interaction between donor and host cells in muscle-derived stem cell mediated bone formation (NIH grant proposal).
3. Evaluation of bone structure and bone defect healing in different animal models of accelerated aging (In collaboration with Drs. B. Wang, M. Lavasani, L. Niedernhofer).

The role of inflammation and angiogenesis in bone formation in different animal models of accelerated aging (NIH grant proposal).

**Administrative Core**  
**(Johnny Huard, James Cummins and Matthew Bosco)**

**INTRODUCTION:**

The Administrative Core of the Stem Cell Research Center (SCRC) is directly responsible for ensuring the proper function and integration of the Research Laboratories (comprising the Core Research Laboratories, Affiliated Laboratories, and Research Core Facilities), the Clinical Trials Unit, and the Educational Programs that constitute the SCRC. The Administrative Core provides administrative services to all SCRC personnel, supports the ongoing activities of the SCRC, and provides a mechanism for regular evaluation of the SCRC. The Administrative Core also is responsible for fulfilling the secretarial, budgetary, and grant application and manuscript preparation needs of SCRC personnel. In addition, this Core also facilitates collaboration between SCRC researchers and scientists working in designated Collaborative Institutes or other, non-affiliated laboratories.

**BODY:**

The Administrative Core continues to provide managerial and financial oversight for the entire Department of Defense Program. The center administrator, Matthew Bosco, and Senior Scientist, James Cummins have played key roles in facilitating and administering all of the various projects within the Program. Mr. Bosco and Mr. Cummins help ensure that each project functions smoothly and efficiently while maintaining continuous communication between the various investigators and institutions.

The Administrative Core organizes a weekly/biweekly seminar series for SCRC (**Table 1**) researchers, affiliates, collaborators, and other interested scientists. The goal of each of these events was to bring in highly regarded scientists who are performing cutting edge research in cellular therapeutics. In addition to serving as a forum in which SCRC scientists can interact with other researchers who share similar interests, this series has helped to introduce the invited speakers to the SCRC and has also helped to promote the development of ongoing collaborations with these well-regarded research scientists. The goal of these meetings is to help SCRC researchers hone their scientific critical analysis skills and, by so doing, improve their own research and writing abilities.

**Table 1**

**SCRC Seminar Series**

<b>Date</b>	<b>Speaker</b>
June 9, 2010	Xueqin Gao
June 23, 2010	Jonathan Pollett
July 7, 2010	Yadong Wang
July 21, 2010	Tom Koloc (respectful workplace)
September 1, 2010	William Chen
September 15, 2010	Kimimasa Tobita
September 29, 2010	Thomas Payne
October 13, 2010	Lei Yang
October 27, 2010	Yong Li
November 10, 2010	
November 24, 2010	
December 8, 2010	Quing Wang
January 5, 2011	
January 19, 2011	ORS

Investigator: Johnny Huard

February 2, 2011	
February 16, 2011	AAOS
February 23, 2011	
March 2, 2011	Paul Robbins

## The use of suramin to improve skeletal muscle healing after contusion injury

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### INTRODUCTION:

Muscle injuries are very common musculoskeletal problems encountered in sports medicine. Although this type of injury is capable of healing, an incomplete functional recovery often occurs, depending on the severity of the blunt trauma. Complete functional recovery is hindered by the development of scar tissue formation, which typically appears during the second week following muscle injury. We have reported that TGF- $\beta$ 1 is a major factor in triggering the fibrotic cascade within injured skeletal muscle [1]. The use of antifibrosis agents, such as suramin, that inactivates TGF- $\beta$ 1 can reduce muscle fibrosis and consequently improve muscle healing after injury. The ability of suramin to block the fibrotic effect of TGF- $\beta$ 1 and reduce the fibrosis makes this molecule well suited for use in applications to improve muscle healing after injury. We already reported that suramin can effectively prevent muscle fibrosis and enhance muscle regeneration in the lacerated and strain-injured muscle [2,3]; however, it is still not known if suramin can improve muscle healing after contusion injury, which is the most commonly encountered muscle injury. Furthermore it has remained unclear whether this enhanced muscle regeneration is a direct effect of suramin. We performed this study to examine whether suramin would promote differentiation of myogenic cells *in vitro* and improve injured muscle healing by enhancing regeneration and reducing fibrosis *in vivo*, using an animal model of muscle contusion.

### MATERIALS AND METHODS:

**Muscle-derived stem cell differentiation assay:** Muscle-derived stem cells (MDSCs) were isolated from wild type mice (C57BL/6J) via the modified preplate technique [4]. MDSCs ( $10^4$  cells/well) were seeded into 12 well plates and were cultured in Dulbecco's modified Eagle's medium (DMEM) containing 10% fetal bovine serum, 10% horse serum, 0.5% chicken embryo extract, and 1% penicillin/streptomycin. After 24 hours, the medium was replaced with differentiation medium (DMEM containing 2% horse serum and 1% penicillin/streptomycin) containing different concentration of suramin (0, 1, 10, 100 $\mu$ l/ml). After another 24 hours, the medium was replaced with only differentiation medium. All cells were grown at 37°C in 5% CO<sub>2</sub>. Three days after incubation the fusion index was assessed by counting the number of nuclei in differentiated myotubes as a percentage of the total number of nuclei.

**Immunocytochemistry in vitro:** Immunocytochemistry was performed on the cells *in vitro* to examine their expression of fast myosin heavy chain (MyHC). Mouse anti-MyHC (1:250; Sigma) was used as the primary antibody, and biotinylated anti-mouse IgG (1:200; Vector) was used as the secondary antibody. Streptavidin 555 conjugate (1:500; Molecular Probes) was applied to detect the secondary antibody.

**Animal model:** The muscle contusion model was developed in normal wild-type mice (7-10 weeks, average weight 24.0g). A 17g stainless steel ball was dropped through an impactor from a height of 100cm onto the animal's tibialis anterior (TA) muscle. Mice were divided into 4 groups (5mice/group). Different concentrations of suramin (0, 2.5, 5, 10mg in 20 $\mu$ l of Phosphate-buffered solution (PBS)) were injected intramuscularly two weeks after injury. Cryostat sections of muscles (10 $\mu$ m in thickness) were obtained and histologically stained (hematoxylin and eosin stain (H&E) and Masson's Trichrome stain) four weeks after injury. The numbers of the centronucleated regenerating myofibers from each group was determined to evaluate the regeneration. Northern Eclipse software (Empix Image, Inc.) was used to quantify the total fibrotic area. Statistical analysis was performed with ANOVA.

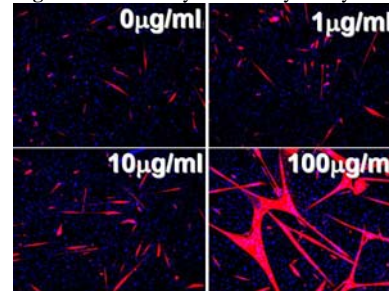
### RESULTS:

**Suramin stimulates MDSCs's differentiation:** Suramin treatment promoted the differentiation of MDSCs *in vitro* in a dose dependent manner. We observed a significantly higher fusion index in each of the two suramin treatment groups (10 and 100 $\mu$ g/ml) than in the control group (0 $\mu$ g/ml). Furthermore, 100 $\mu$ g/ml of suramin treatment enhanced the differentiation significantly more than the other suramin treatments (1 and 10 $\mu$ g/ml) (Fig.1,2).

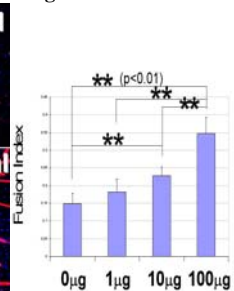
**Suramin enhances muscle regeneration and decreases fibrosis after contusion injury:** We observed a significant increase in the number of regenerating myofibers in all of suramin treated groups (2.5, 5, 10mg/

20 $\mu$ l PBS) when compared with the control group (0mg/20 $\mu$ l of PBS) (Fig. 3,4). Moreover Masson's Trichrome staining showed significantly less fibrotic area in all of suramin treated groups than in the control group (Fig. 5, 6). Although all three suramin treated groups showed significant improvement in healing by way of muscle regeneration and fibrosis inhibition, there was no significant difference between the three suramin treatment groups (data not shown).

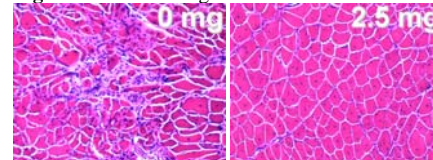
**Figure 1. Immunocytochemistry of MyHC**



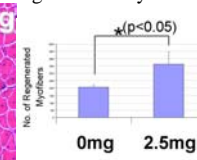
**Figure 2. Fusion Index**



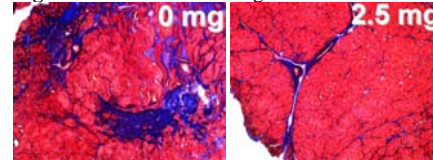
**Figure 3. H-E staining 4 wks after contusion**



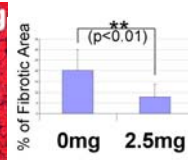
**Figure 4. Number of regenerated myofibers**



**Figure 5. Trichrome staining after contusion**



**Figure 6. Percentage of Fibrotic area**



### DISCUSSION:

We have reported that suramin can effectively prevent muscle fibrosis and enhance muscle regeneration after laceration and strain injury. Furthermore, our preliminary data has indicated that suramin blocks the proliferative effect of TGF- $\beta$ 1 on fibroblasts *in vitro* [2,3]. We examined the effect of suramin on the differentiation of MDSCs after we observed that suramin enhanced the differentiation of C2C12 as a preliminary study. Our results from this experiment showed that the suramin treated MDSC groups have higher fusion indices than the control group *in vitro*. This indicates that suramin can enhance the differentiation of MDSCs, revealing part of the mechanism by which suramin enhances the muscle regeneration after injury. This is the first study to show that suramin is affecting the differentiation of MDSCs directly in addition to its antiproliferative effect on fibroblasts. Furthermore, our result shows suramin can enhance muscle regeneration and prevent fibrosis after a contusion injury, the most common muscle injury. Our future study will investigate the mechanism by which suramin enhances the differentiation of myogenic cells.

### Acknowledgements:

The authors are grateful for technical assistance from Maria Branca, Jessica Tebbets, and Aiping Lu. Funding support was provided by a grant from the Department of Defense (W81XWH-06-1-0406).

### References:

- Li Y, Foster W *et al.*, *Am J Pathol* 2004;164: 1007-19.
- Chan Y, Li Y *et al.*, *J Appl Physiol* 2003;95:771-80.
- Chan Y, Li Y *et al.*, *Am J Sports Med* 2005; 33:43-51.
- Qu-Peterson Z, *et al.*, *J Cell Bio* 2002; 157: 851-64.

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# Decorin Gene Transfer Promotes Muscle Cell Differentiation and Muscle Regeneration

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<sup>4</sup>Department of Molecular Genetics and Biochemistry, University of Pittsburgh, Pittsburgh, Pennsylvania, USA

We have shown that decorin, a small leucine-rich proteoglycan, can inhibit transforming growth factor (TGF)- $\beta$ 1 to prevent fibrous scar formation and improve muscle healing after injury. In the decorin-treated muscle, an enhancement of muscle regeneration is observed through histological examination. In this article, we report our determination of whether decorin has a direct effect on myogenic cells' differentiation. Our results indicate that myoblasts genetically engineered to express decorin (CD cells) differentiated into myotubes at a significantly higher rate than did control myoblasts (C2C12). This enhanced differentiation led to the up-regulation of myogenic genes (*Myf5*, *Myf6*, *MyoD*, and myogenin) in CD cells *in vitro*. We speculate that the higher rate of differentiation exhibited by the CD cells is due to the up-regulation of follistatin, peroxisome-proliferator-activated receptor-gamma co-activator-1 $\alpha$  (PGC-1 $\alpha$ ), p21, and the myogenic genes, and the down-regulation of TGF- $\beta$ 1 and myostatin. Decorin gene transfer *in vivo* promoted skeletal muscle regeneration and accelerated muscle healing after injury. These results suggest that decorin not only prevents fibrosis but also improves muscle regeneration and repair.

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## INTRODUCTION

Decorin, a small leucine-rich proteoglycan, is a component of the extracellular matrix of all collagen-containing tissues.<sup>1</sup> Decorin is pivotal in regulating the proper assembly of collagenous matrices and in controlling cell proliferation under various conditions.<sup>2</sup> On the basis of its ability to bind fibrillar collagen and delay *in vitro* fibrillogenesis, decorin is regarded as a key modulator of matrix assembly.<sup>3,4</sup> This proteoglycan can modulate the bioactivity of growth factors and act as a direct signaling molecule to different cells.<sup>5</sup> Decorin, which is expressed at high levels in skeletal muscle during early development,<sup>6</sup> also interferes with muscle cell differentiation and migration and regulates connective tissue formation in skeletal muscle.<sup>7–9</sup>

Because terminal differentiation is critical for initial skeletal muscle development and regeneration after injury and disease,<sup>10</sup> we examined decorin's role in remodeling healing skeletal muscle. We have shown that the direct injection of bovine decorin decreased muscle fibrosis and provided nearly complete functional recovery.<sup>11</sup> Decorin blocks fibrosis (mostly by inhibiting transforming growth factor (TGF)- $\beta$  activity), which improves muscle healing. However, the role of decorin in muscle cell differentiation and regeneration is still unknown. Although we hypothesize that decorin's effect on muscle fibrosis may indirectly impact regeneration, we were unable to exclude the possibility that decorin promotes regeneration independent of its effects on fibrosis formation.

Many studies have investigated the mechanism behind the antifibrotic effect of decorin.<sup>3,12–14</sup> Others have shown that hepatocyte growth factor increases decorin production by fibroblasts through the extracellular signal-regulated kinase 1/2, and p38 mitogen-activated protein kinase-mediated pathways.<sup>14</sup> Decorin stimulates the growth of smooth muscle cells under specific conditions and influences the growth of epidermal cells by interacting with epidermal growth factor and its receptors.<sup>15,16</sup> Recent research has shown that decorin can bind both insulin-like growth factor-I and its receptor; this interaction leads to the phosphorylation of protein kinase B (Akt) and p21 expression in endothelial cells.<sup>17</sup>

Decorin also influences muscle cell behavior by interacting with p21, an important cyclin-dependent kinase inhibitor.<sup>18,19</sup> Follistatin and myostatin are involved in the control of muscle mass during development. These two proteins have opposite effects on muscle growth, as documented by genetic models.<sup>21,22</sup> Recent studies have shown that myostatin action is inhibited by decorin,<sup>23</sup> resulting in enhanced healing and reduced fibrosis within myostatin-null mice compared with wild-type mice.<sup>24</sup> A recent study indicates that peroxisome-proliferator-activated receptor-gamma co-activator-1 $\alpha$  (PGC-1 $\alpha$ ), is also involved in the muscle healing process and influences muscle fiber-type determination.<sup>25,26</sup> Decorin may also interact with PGC-1 $\alpha$  expression in skeletal muscle after injury.

In this study, we investigated the *in vitro* effect of decorin on the differentiation of myoblasts (C2C12) and characterized the *in vitro* and *in vivo* behavior of myoblasts transfected with the



decorin gene (CD cells). We also studied the influence that decorin over-expression had on myostatin, follistatin, PGC-1 $\alpha$ , and p21 expression. Using an adeno-associated virus (AAV) vector, we transduced the decorin gene into injured skeletal muscle to further investigate its function on muscle healing. Our overall goal in this study was to determine whether decorin could improve skeletal muscle healing by enhancing muscle regeneration independently of its antifibrotic action.

## RESULTS

### Genetic engineering of myogenic cells to over-express decorin

We used lipofectin to transfect a pAAV-CMV-decorin plasmid (Figure 1a) into both 293 cells (packaging cell line) and C2C12 cells (myoblast cell line). The results of western blot analysis (Figure 1b) showed decorin in both the supernatant (culture media) and the lysate of the 293 cells 48 hours after transfection. The transfected C2C12 cells (CD clone cells) expressed decorin (Figure 1c: lane 2, 24 hours; lane 4, 48 hours; lane 5, decorin-positive control), whereas non-transfected C2C12 cells did not (Figure 1c: lane 1, 24 hours; lane 3, 48 hours). We also detected decorin in both myoblasts (C2C12) and muscle-derived stem cells after mDecorin-AAV (mDec-AAV) gene transfer *in vitro* (Figure 1d and e).

### Decorin stimulates myoblast differentiation *in vitro*

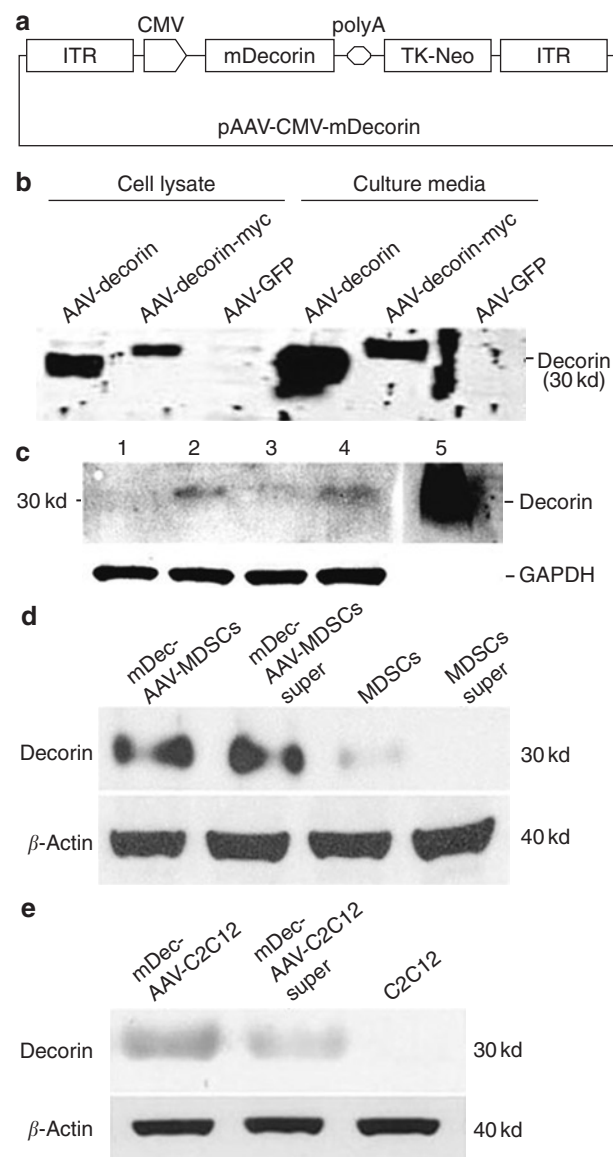
To investigate myoblast differentiation, we compared decorin-co-cultured C2C12 cells with non-treated C2C12 cells *in vitro*. C2C12 cells cultured with decorin (10  $\mu$ g/mL) and grown in differentiation/fusion medium exhibited significantly enhanced differentiation and fusion *in vitro*. After 3 and 4 days of stimulating C2C12 cells with decorin, we observed a significant increase in the number of myotubes when compared with un-stimulated C2C12 (control) cells ( $P < 0.01$  at 3 days and  $P < 0.05$  at 4 days, respectively). However, the numbers of myotubes 5 days after treatment were not significantly different (Figure 2a). We then evaluated whether CD cells exhibited a greater propensity to undergo myogenic differentiation than did non-transfected C2C12 cells. As shown in Figure 2b (myotubes stained in mouse anti-myosin heavy chain are red) and Figure 2c, CD cells generated significantly more myotubes overall and created significantly larger myotubes than did non-transfected C2C12 cells.

### Decorin increases myoblast differentiation and induces myogenic gene expression *in vitro*

We investigated whether the CD cells expressed higher levels of myogenic genes than did non-transfected C2C12 (control) cells. Our results, shown in Figure 3a, demonstrate that decorin gene transfer led to higher expression of the myogenic genes *Myf5*, *Myf6*, *MyoD*, and *myogenin*. Desmin expression levels in CD and C2C12 cells remained similar.

### Decorin up-regulates p21, follistatin, and PGC-1 $\alpha$ , but down-regulates TGF- $\beta$ 1 and myostatin in C2C12

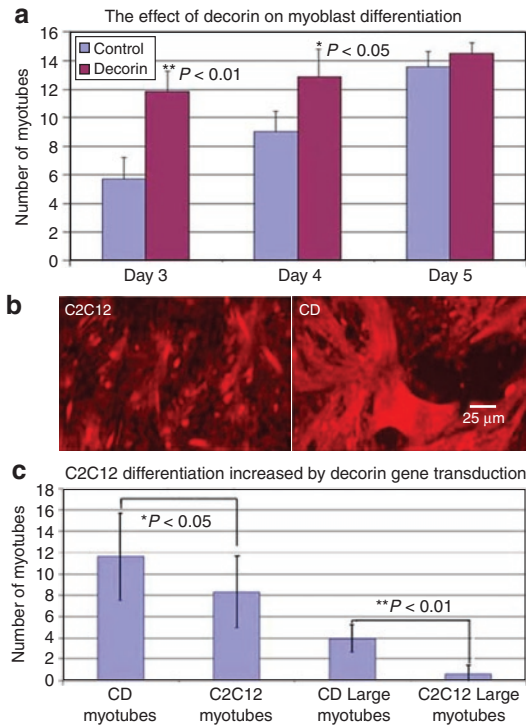
We also performed experiments designed to investigate the mechanism by which decorin influences the differentiation of muscle cells. We found that CD cells exhibited increased p21



**Figure 1** Decorin plasmid construction and initial transfection *in vitro*. (a) The decorin plasmid used for the study contained the full sequence of a mouse decorin gene inserted at the *NotI* site, which placed it under the control of a cytomegalovirus (CMV) promoter. (b) We transfected the plasmid into 293 cells. We observed decorin expression in both the 293 cells and their supernatant, but not in the control adeno-associated virus (AAV)-transfected (green fluorescent protein, GFP) cells. (c) Western blot analysis also revealed decorin expression in CD clone cells within different time period cultures (lane 2, 24 hours; lane 4, 48 hours), but not in C2C12 (lane 1, 24 hours; lane 3, 48 hours). We used 5  $\mu$ g of decorin as a positive control (lane 5). GAPDH, glyceraldehyde-3-phosphate dehydrogenase is used as a control. (d) Decorin expression in muscle-derived stem cells (MDSCs) in pellet form was low, but this was not the case in the supernatant. Both MDSCs and their cultured supernatant strongly expressed decorin after mDec-AAV gene transfer.  $\beta$ -actin is used as a control. (e) We did not detect decorin in normal C2C12 cells, but C2C12 cells and their cultured supernatant both expressed decorin after mDec-AAV gene transfer.

expression and decreased myostatin expression (Figure 3b). The C2C12 cells can be induced to express TGF- $\beta$ 1 in an auto-crine manner, as we have previously determined;<sup>27</sup> however, the CD cells do not show any detectable expression of TGF- $\beta$ 1 after





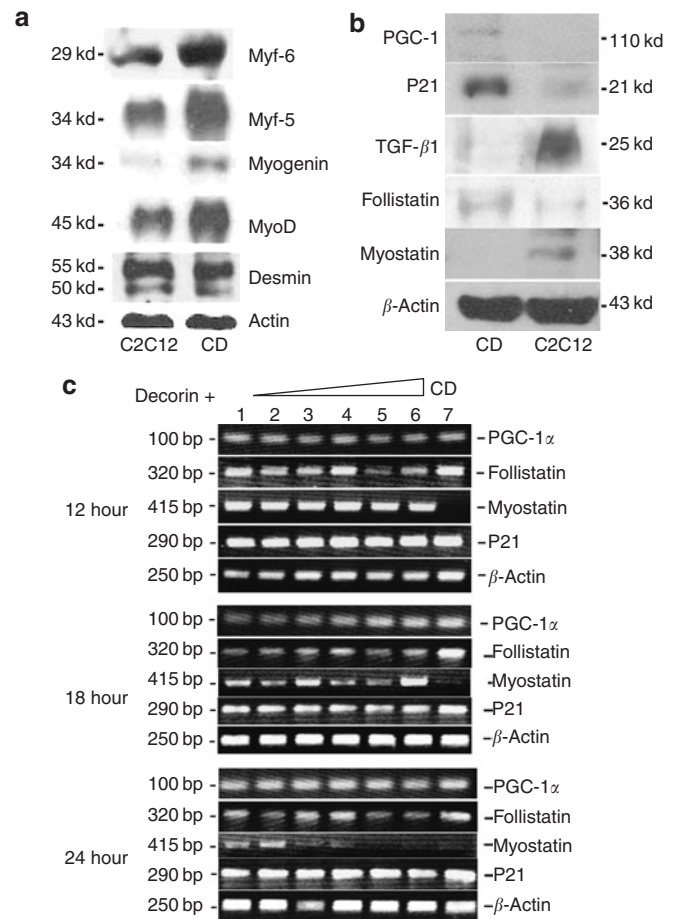
**Figure 2** Decorin stimulates C2C12 differentiation *in vitro*. **(a)** Decorin treatment accelerated the differentiation and fusion of myoblasts (C2C12 cells) compared with non-treated myoblasts (C2C12 cells). **(a)** The cultures of decorin-treated C2C12 cells contained more myotubes at the 3- and 4-day time points than control cells. **(b, c)** Similarly, decorin-transfected C2C12 clone cells (CD cells) produced more myotubes than did C2C12 cells, including larger myotubes (containing more than three nuclei) *in vitro*. Red staining shows myosin heavy chain fluorescence after immunostaining **(b)**.

TGF- $\beta$ 1 stimulation. More importantly, we detected that both follistatin and PGC-1 $\alpha$  (Figure 3b) had been up-regulated when compared with C2C12 cells. We also discovered that follistatin and PGC-1 $\alpha$  messenger RNA were altered in C2C12 cells after decorin stimulation, as determined by real-time polymerase chain reaction. Specifically, we found that PGC-1 $\alpha$  and follistatin increased in a dose-dependent manner after 18 hours of stimulation with decorin, and that myostatin was decreased in a dose-dependent manner after 24 hours of stimulation with decorin (Figure 3c). In CD cells, we also observed increased amounts of all three genes (*p21*, *follistatin*, and *PGC-1 $\alpha$* ), but a decrease in myostatin was observed (Figure 3c).

The up-regulation of *follistatin*, *PGC-1 $\alpha$* , *p21*, and myogenic genes, including *MyoD* (Figure 3a), in CD cells could at least partially explain how decorin promotes muscle cell differentiation. Alternatively, the down-regulation of myostatin, a well-known negative regulator of muscle growth during muscle regeneration, could also benefit muscle cell differentiation.

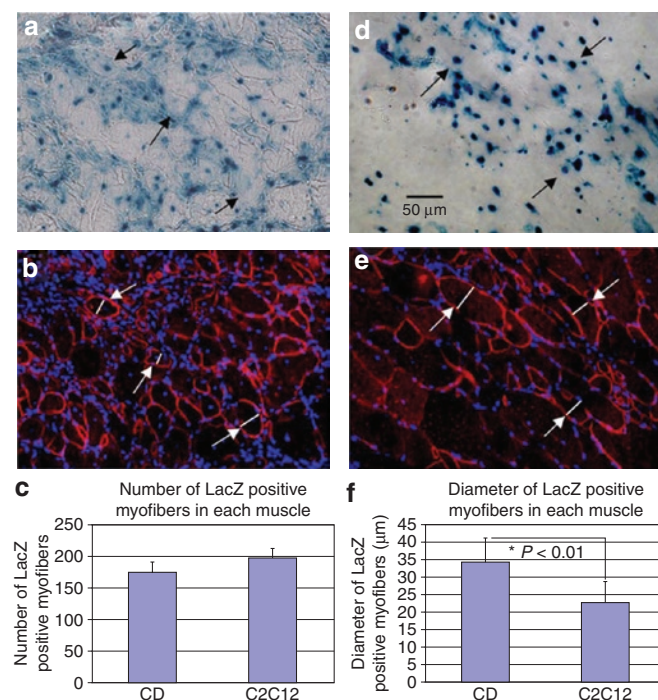
### The implantation of CD cells in skeletal muscle results in improved muscle regeneration

The implantation of CD cells within skeletal muscle resulted in significantly better muscle regeneration than that observed for control C2C12 cells, as determined 4 weeks after injection of the cells into MDX/SCID mice. Although the number of LacZ-positive



**Figure 3** Decorin gene transfer up-regulates myogenic proteins and *p21* and down-regulates myostatin during muscle cell differentiation. **(a)** Genetic engineering of myoblasts to express decorin influenced the expression of myogenic proteins (including Myf5/6, Myogenin, and MyoD), as shown by western blot results. However, C2C12 cells and CD clone cells expressed comparable levels of desmin. **(b)** We detected the presence of *p21* expressed in CD clone cells. We also detected peroxisome-proliferator-activated receptor- $\gamma$  co-activator-1 $\alpha$  (PGC-1 $\alpha$ ) and follistatin expressed in CD, but not C2C12, cells. In addition, CD cells exhibited lower levels of myostatin, a negative regulator of muscle mass. The induction of tumor growth factor (TGF)- $\beta$ 1 auto-expression was also inhibited by decorin over-expression in CD cells. **(c)** Similar results were obtained by real-time polymerase chain reaction. Lanes 1–6 show results for C2C12 cells exposed to different concentrations of decorin (0, 0.001, 0.01, 0.1, 1.0, and 5.0 ng/ml, respectively). Lane 7 displays the test results for CD cells, which served as the positive control. We did not detect a visible change in the expression of PGC-1 $\alpha$ , follistatin, myostatin, or *p21* after 12 hours of stimulation with different concentrations of decorin. PGC-1 $\alpha$  and follistatin were up-regulated in C2C12 cells in a dose-dependent manner after 18 hours of stimulation with decorin. Myostatin was down-regulated in C2C12 cells in a dose-dependent manner after 24 hours of decorin stimulation. The concentration of *p21* did not visibly change after cell stimulation with any experimental concentration of decorin over all time points. With decorin gene transfer, we found that CD cells consistently expressed follistatin, *p21*, and PGC-1 $\alpha$  but were negative for myostatin. Note that  $\beta$ -actin was selected as a positive gene control.

muscle fibers (*i.e.*, regenerating muscle fibers) did not differ between the groups (Figure 4a, c, and d), the diameters of the regenerating muscle fibers (*e.g.*, dystrophin-positive myofibers) in the muscles injected with CD cells were significantly larger than those of the regenerating muscle fibers in the control muscles



**Figure 4** Decorin gene transfer stimulates muscle regeneration *in vivo*. C2C12 cells regenerated muscle fibers after transplantation into skeletal muscle of MDX/SCID mice, as shown on both (a) LacZ- and (b) dystrophin-expressing myofibers. However, transplantation of CD clone cells, rather than C2C12 cells, resulted in larger muscle fibers in MDX/SCID mice, as shown in some of the (d) LacZ- and (e) dystrophin-positive myofibers. (c) Although there was no significant difference between the number of LacZ-labeled muscle fibers that formed in muscles transplanted with C2C12 or CD cells, (f) the transplantation of CD cells resulted in the regeneration of larger-diameter myofibers ( $P < 0.01$ ).

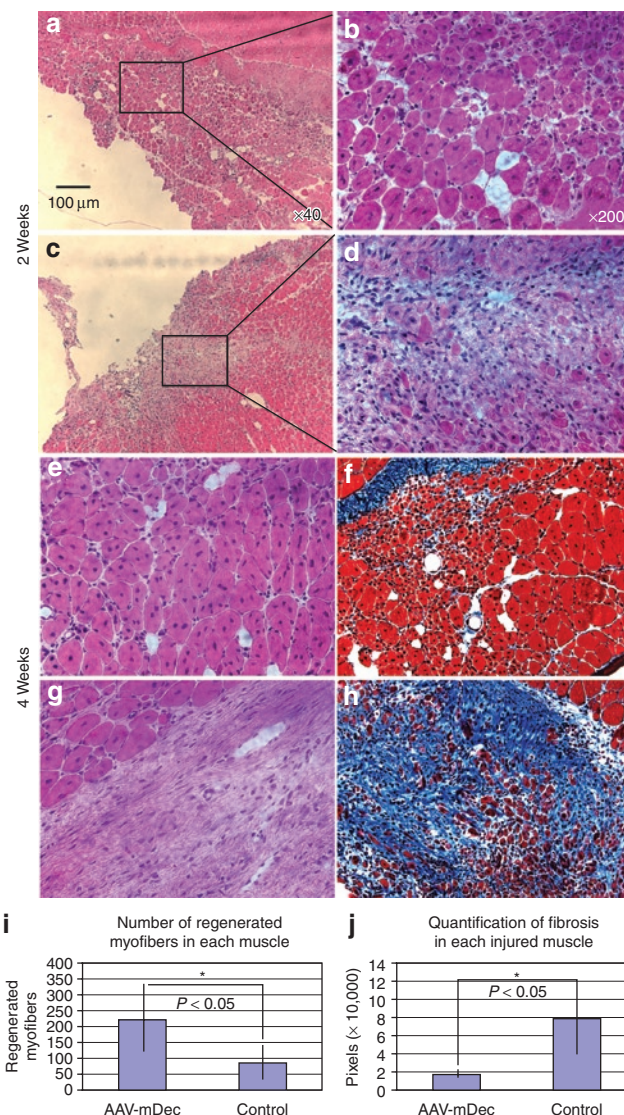
(Figure 4b, e, and f; dystrophin is red). The larger diameters of the dystrophin-positive muscle fibers generated by CD cells could indicate that implantation of CD cells accelerated muscle regeneration; however, we were unable to exclude the possibility that the CD cells may have a greater propensity to fuse in host myofibers than C2C12 control cells.

### mDec-AAV gene transfer promotes muscle regeneration and reduces fibrosis

Better muscle regeneration was observed within mDec-AAV-treated muscle (Figure 5a and b) than within non-mDec-AAV-treated muscle at 2 weeks after injury (Figure 5c and d). Histological analysis of total collagen deposition 4 weeks after injury revealed that mDec-AAV-injected muscles contained less fibrous scar tissue in the injured area than did non-treated control muscles (Figure 5f, h, and j; collagen deposition areas are blue). We also observed that decorin stimulated skeletal muscle regeneration 4 weeks after laceration injury. We found that mDec-AAV-injected muscles contained more centronucleated (regenerating) myofibers and less scar tissue 4 weeks after injury than did control muscles (Figure 5e, g, and i).

### DISCUSSION

Results from these experiments show that decorin is able to activate the differentiation of skeletal muscle cells (C2C12) *in vitro*

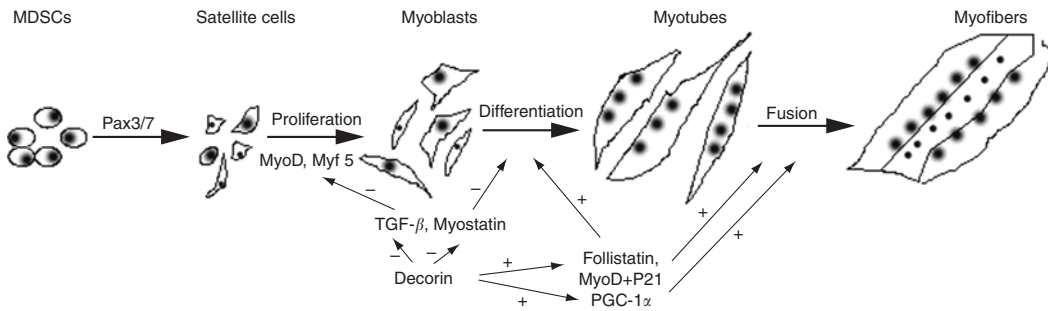


**Figure 5** mDec-AAV vector gene therapy in injured muscle prevents fibrosis and promotes muscle regeneration. Decorin-treated muscle exhibits a greater number of regenerating myofibers than the control muscle at all time points (a–d 2 weeks; e–h 4 weeks). (i) The mDec-AAV-injected muscle contained significantly higher numbers of centronucleated (regenerated) myofibers than did control (sham-injected) muscle at 4 weeks after therapy. We also found that decorin gene therapy minimized fibrosis in injured skeletal muscle. We used Masson's trichrome staining to reveal collagen in injured skeletal muscle, the results of which show that (f) mDec-AAV-injected muscle contained significantly less fibrosis in the injured area than did the (h) control muscle at (j) 4 weeks after injury.

and enhances muscle regeneration in two mouse models *in vivo*. The mechanism behind decorin's accelerated muscle healing is not yet known; however, our results demonstrate that decorin up-regulates the expression of PGC-1 $\alpha$ , follistatin, p21, and a variety of myogenic proteins (including MyoD) but down-regulates myostatin expression. These results, in addition to decorin's ability to neutralize the effects of TGF- $\beta$ 1, likely explain the beneficial action that decorin has on muscle cell differentiation and muscle regeneration.

Our previous studies have demonstrated that myogenic cells (including muscle-derived stem cells) in injured muscle can





**Figure 6** Schematic of the potential effect of decorin on muscle healing. Decorin may improve muscle healing through various pathways: inhibition of tumor growth factor (TGF)- $\beta$ 1, up-regulation of follistatin, peroxisome-proliferator-activated receptor- $\gamma$  co-activator-1 $\alpha$  (PGC-1 $\alpha$ ), p21, and myogenic genes (such as *MyoD*), and down-regulation of myostatin expression. MDSCs, muscle-derived stem cells.

differentiate into fibrotic cells and that TGF- $\beta$ 1 is a major stimulator of this differentiation.<sup>27,28</sup> Using different animal models of muscle injury, we have investigated biological approaches to prevent fibrosis and thereby improve muscle healing.<sup>11,27,29–31</sup> We have used various molecules, such as decorin, that impede fibrosis by blocking TGF- $\beta$ 1 to facilitate the near-complete recovery of injured skeletal muscle.<sup>11</sup> The ability of decorin to inhibit TGF- $\beta$ 1 activity is the likely mechanism by which this molecule blocks fibrosis formation. However, our results indicate that the improved muscle healing observed after decorin treatment is due to both its inhibiting effect on fibrosis and its stimulating effect on muscle regeneration. **Figure 6** summarizes the potential effect of decorin on muscle healing.

The repair of injured skeletal muscle occurs through the activation of muscle precursor cells located between the basal lamina and the sarcolemma, including satellite cells and stem cells.<sup>32</sup> The activation and growth of these cells are regulated by various growth factors released by infiltrating lymphocytes, injured myofibers, and the extracellular matrix.<sup>10,32</sup> Some growth factors, such as insulin-like growth factor-1 and hepatocyte growth factor, can stimulate precursor cell proliferation and differentiation by increasing the transcriptional activity of the muscle basic helix–loop–helix.<sup>33–36</sup> Healing and organizational processes are dependent upon the extra- and intracellular signaling that induces the expression of myogenic genes, including *MyoD*, *Myf5*, and *myosin*.<sup>37,38</sup> When properly stimulated, precursor cells fuse with one another or with local myofibers to repair the damaged muscle.<sup>39</sup>

Muscle regeneration, the key event in muscle healing, is often incomplete, particularly in severely injured muscle.<sup>10,11,27,28,32,40</sup> The overgrowth of the extracellular matrix leads to significant local fibrosis (*i.e.*, fibrous scar formation) in the injured area, which can impede the formation of normal muscle fibers. The presence of fibrous scar tissue in injured muscle results in incomplete functional recovery and a propensity for re-injury.<sup>41</sup> Muscle regeneration and fibrosis in injured muscle often occur simultaneously and thus compete with one another during the muscle healing process.<sup>32,36,40</sup> A persistent imbalance between collagen biosynthesis and degradation contributes to hypertrophic scar formation and fibrosis in many tissues.<sup>42,43</sup> Several studies have revealed high levels of collagen in injured regions of skeletal muscle, and shown that inhibition of collagen deposition reduced the formation of scar tissue in injured skeletal muscle.<sup>27,28,30,31</sup>

Interactions between decorin and TGF- $\beta$ 1 have been observed in many tissues, and researchers have used various animal models to study the antifibrotic effect of decorin.<sup>3,11,13,44</sup> Researchers have also shown that hepatocyte growth factor can increase the level of decorin expression in fibroblasts, perhaps by activating the extracellular signal-regulated kinase 1/2 and p38 mitogen-activated protein kinase-mediated pathways.<sup>14</sup> Such findings could explain the antifibrotic effect of hepatocyte growth factor in a variety of tissues.<sup>14,45–47</sup> In endothelial cells, decorin binds with both insulin-like growth factor-1 and its receptor to influence cell behavior.<sup>17</sup> Decorin can also control and suppress cancer growth and invasion, presumably by influencing the biological activity of growth factors such as TGF- $\beta$ 1, platelet-derived growth factor, vascular endothelial growth factor, and epidermal growth factor, all of which are released by cancer cells.<sup>5,15</sup> These decorin-induced effects appear to be mediated, at least in part, by a specific interaction between the decorin protein core and the epidermal growth factor receptor.<sup>15,16</sup> This interaction triggers a signal cascade that results in activation of mitogen-activated protein kinase, mobilization of intracellular calcium, up-regulation of p21, and, ultimately, the suppression of tumor growth.<sup>18,19</sup>

Cell cycle exit and the differentiation of muscle cells are coordinated by p21, which is essential for normal myogenic progenitor cell differentiation and skeletal muscle regeneration. Studies have indicated that p21 is necessary for MyoD-induced activity in cells, allowing them to enter into and be stabilized in a post-mitotic state. Since MyoD plays a central role in the differentiation of muscle cells, TGF- $\beta$ 1 controls myostatin-related regulation of myogenesis in muscle cells by down-regulating both p21 and MyoD. In this study, we determined that the treatment of myoblasts with decorin down-regulated the expression of myostatin, which might influence p21 and myogenic protein expression. In addition, myostatin and follistatin interact directly in the skeletal muscle system. Follistatin can inhibit myostatin, leading to muscle differentiation in a concentration-dependent manner.<sup>21</sup> PGC-1 $\alpha$ , which is expressed in several tissues, including brown fat and the skeletal muscle of mammals, activates mitochondrial biogenesis and oxidative metabolism.<sup>26</sup> PGC-1 $\alpha$  is a principal factor involved in determining muscle fiber type in injured skeletal muscle and is involved in exercise-induced mitochondrial biogenesis.<sup>48</sup> In this experiment, we observed that decorin treatment increased PGC-1 $\alpha$  expression in skeletal muscle cells. Combined with our previous research results, our current findings suggest that decorin not

only acts as an antifibrotic agent but also enhances muscle regeneration in skeletal muscle.

Successful muscle differentiation during limb development requires decorin expression.<sup>6</sup> Previous findings have shown that decorin can improve muscle healing by inhibiting fibrosis and that myoblasts and muscle satellite cells expressing decorin in an injured site regenerated damaged myofibers faster than the controls.<sup>11,27</sup> The results of this study demonstrate that decorin is also a potent stimulator of skeletal muscle regeneration. Myoblasts expressing decorin differentiated and fused to form myotubes and myofibers at a significantly higher rate than did normal myoblasts *in vitro* and *in vivo*. We attribute this enhanced differentiation to the up-regulation of p21, follistatin, PGC-1 $\alpha$ , and myogenic gene expression and the down-regulation of TGF- $\beta$ 1 and myostatin. These results provide at least a partial explanation of the way in which decorin promotes muscle regeneration and may explain why there is such a high level of decorin expression in developing skeletal muscle. It is possible that decorin increases muscle fiber growth and limits the overgrowth of connective tissues. These findings indicate that decorin could be very useful in promoting the healing of muscles damaged by injury or disease.

## MATERIALS AND METHODS

**Gene transfection and transfer.** An AAV-mDecorin plasmid, which encodes for a mouse decorin sequence under the control of the cytomegalovirus promoter (Figure 1), was used for gene transfection. This plasmid also contains a neomycin resistance gene to enable G418 selection. The AAV-mDecorin plasmid was transfected into 293 packaging cells and C2C12 cells with lipofectin; clone cells were selected for treatment of the cells with G418 (500  $\mu$ g/mL) (Gibco BRL, Grand Island, NY) for 2 weeks. The selected decorin-transfected C2C12 clone cells (CD cells) were cultured in Dulbecco's modified Eagle's medium (Gibco BRL, Grand Island, NY) containing the same concentration of G418 for the remainder of the project.

The mDec-AAV vector was produced by co-transfection methods described previously by Dr. Xiao.<sup>49</sup> Muscle-derived stem cells and myoblasts (C2C12 cells) were each grown to 50–60% confluency. Fresh Dulbecco's modified Eagle's medium (without fetal bovine serum or penicillin/streptomycin) containing the mDec-AAV vector ( $5 \times 10^4$  particles/cell) was then added directly to the cells. The cultures were incubated at 37°C in a 5% CO<sub>2</sub> incubator for 1 hour. Normal culture medium (Dulbecco's modified Eagle's medium supplemented with 10% fetal bovine serum and 1% Abs) was then added for another 24 hours, at which point the cells were collected for analysis of decorin expression by western blotting.

**Differentiation of myoblasts and immunocytochemistry.** Three different groups of cells (C2C12 cells, C2C12 cells cultured with decorin, and CD cells) were seeded into 12-well plates containing proliferation medium.<sup>28</sup> All cells were transferred into serum-free medium 12 hours later to induce differentiation. The myotubes that formed in the cultures were counted daily for 5 days, and the numbers were compared among the groups. We considered myotubes containing three or more nuclei to be large myotubes *in vitro*. At different time points, the cells were fixed with cold acetone (3 minutes) for immunostaining. Mouse anti-myosin heavy chain antibody (Novocastra Lab) at a 1:200 dilution was applied for 1 hour at room temperature (RT). The primary antibody was detected using anti-mouse-Cy3, 1:250 for 45 minutes at RT. Results were analyzed by fluorescent microscopy (Nikon microscope, Nikon, Melville, New York).

**Real-time polymerase chain reaction.** Total RNA was extracted from the treated and non-treated C2C12 cells using a Nucleospin column (Clontech, Mountain View, CA), and the complementary DNA was synthesized with

SuperScript II reverse transcriptase (Invitrogen, Carlsbad, CA), both according to manufacturer's instructions. Primers specific for *myostatin*, *follistatin*, *p21*, and *PGC-1 $\alpha$*  were designed using Oligo software (OligoPerfect Designer; Invitrogen, Carlsbad, CA). The protocol for amplification was as follows: 94°C for 30 seconds, 58°C for 30 seconds, and 72°C for 30 seconds for 30 cycles. Polymerase chain reaction products were separated by size in a 1.5% agarose gel.

**Western blot analysis.** C2C12 and CD cells were lysed when cell density reached 70% confluency. The samples were separated on a 12% sodium dodecyl sulfate–polyacrylamide electrophoresis gel and transferred to nitrocellulose membranes used to perform immunostaining. The primary antibodies were anti-decorin (a gift from Dr. Fisher of the National Institutes of Health), anti-TGF- $\beta$ 1 (4  $\mu$ g/mL; BD Pharmingen, San Diego, CA), anti-p21 (BD Pharmingen, San Diego, CA), anti-myf5, anti-myf6, anti-MyoD, and anti-myogenin (Santa Cruz Bio, Santa Cruz, CA), all at concentrations of 1:1,000, and anti-myostatin, anti-follistatin (Chemicon, Temecula, CA), and anti-desmin (Sigma, St. Louis, MO), all at concentrations of 1:2,000 for 1 hour at RT. Mouse anti- $\beta$ -actin and anti-glyceraldehyde-3-phosphate dehydrogenase (Sigma, St. Louis, MO) were used for protein quantification and were diluted to 1:8,000. The secondary anti-rat horseradish peroxidase or anti-rabbit horseradish peroxidase (Pierce, Rockford, IL) was used at a concentration of 1:5,000 for 1 hour. Peroxidase activity was determined by enhanced chemiluminescence (Amersham Pharmacia Biotech, Piscataway, NJ), and the positive bands were detected on X-ray film. Northern Eclipse software v.6.0 (Empix Imaging, Mississauga, Canada) was used to evaluate all results.

**Animal experiments.** All animal experiments were approved by the Children's Hospital of Pittsburgh. The Animal Research Committee at the authors' institution approved all experimental protocols (No. 15/03).

**Group 1: C2C12 and CD cell transplantation.** Twenty-four female MDX/SCID mice (C57BL/10ScSn-Dmd<sup>mdx</sup> crossed with C57BL/6J-Prkdc<sup>scid</sup>/SzJ, 6–8 weeks of age) were used for the C2C12 and CD cell transplantation. C2C12 and CD clone cells were transduced with a retrovirus vector encoding for LacZ.<sup>27</sup> LacZ-positive CD cells ( $1 \times 10^6$ ) were injected into the left gastrocnemius muscles (GMs); the same quantity of LacZ-positive C2C12 cells were injected into the right GMs as a control. At various times after injection, mice were killed, and the GMs were collected for histological analysis by LacZ staining and immunohistochemistry to stain for dystrophin-positive myofibers.

**Group 2: mDec-AAV gene therapy administered to injured skeletal muscle.** Twenty mice (C57BL6J)<sup>+/+</sup>, 6 weeks old; Jackson Laboratory, Bar Harbor, ME) were used for these experiments. The mDec-AAV vector ( $2 \times 10^{11}$  particles in 20  $\mu$ L of Dulbecco's modified Eagle's medium) was injected directly into the left GM of each mouse; the contralateral leg was injected with the same volume of phosphate-buffered saline (20  $\mu$ L) as a control. One week after injection, both GMs were lacerated in accordance with our previously described muscle injury model.<sup>11,27,28,40</sup> Mice were killed at different time points (5 days and 1, 2, 3, and 4 weeks after injury), and the GMs were collected for histological analysis by either hematoxylin and eosin or Masson's trichrome staining. The regeneration and fibrous scar tissue formation in the two groups were compared.

**Immunohistochemical analysis.** Serial 10- $\mu$ m cryostat sections were prepared using standard techniques.<sup>27,28</sup> For immunohistochemistry, the slides were fixed with formalin (4%) for 5 minutes after LacZ staining, and then blocked with donkey serum (10%) for 1 hour. Rabbit anti-dystrophin antibody (Abcam, Cambridge, MA) was applied to the slides at a 1:300 dilution for 60 minutes at RT. The second antibody, goat anti-rabbit IgG (Alexa Fluor® 488; Molecular Probes, Eugene, OR), was used at a concentration of 1:200 for 45 minutes at RT. Negative controls were performed concurrently with all immunohistochemical staining. The nuclei of the sections were revealed using 4',6'-diamidino-2-phenylindole hydrochloride

staining (Sigma, St. Louis, MO), and fluorescent microscopy was used to visualize the results as described above.

**Statistical analysis.** LacZ-positive myofibers were counted in 10 representative sections. Both the diameter and number of LacZ- and dystrophin-positive myofibers were assessed at different time points in each group. The statistical significance of differences between the various groups was determined using a *t*-test or one-way or two-way analysis of variance.

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## REFERENCES

- Hocking, AM, Shinomura, T and McQuillan, DJ (1998). Leucine-rich repeat glycoproteins of the extracellular matrix. *Matrix Biol* **17**: 1–19.
- Sottile, J, Hocking, DC and Swiatek, PJ (1998). Fibronectin matrix assembly enhances adhesion-dependent cell growth. *J Cell Sci* **111**: 2933–2943.
- Giri, SN, Hyde, DM, Braun, RK, Gaarde, W, Harper, JR and Pierschbacher, MD (1997). Antifibrotic effect of decorin in a bleomycin hamster model of lung fibrosis. *Biochem Pharmacol* **54**: 1205–1216.
- Noble, NA, Harper, JR and Border, WA (1992). *In vivo* interactions of TGF-beta and extracellular matrix. *Prog Growth Factor Res* **4**: 369–382.
- Stander, M, Naumann, U, Dumitrescu, L, Heneka, M, Loschmann, P, Gulbins, E *et al.* (1998). Decorin gene transfer-mediated suppression of TGF-beta synthesis abrogates experimental malignant glioma growth *in vivo*. *Gene Ther* **5**: 1187–1194.
- Nishimura, T, Futami, E, Taneichi, A, Mori, T and Hattori, A (2002). Decorin expression during development of bovine skeletal muscle and its role in morphogenesis of the intramuscular connective tissue. *Cells Tissues Organs* **171**: 199–214.
- Brandan, E, Fuentes, ME and Andrade, W (1991). The proteoglycan decorin is synthesized and secreted by differentiated myotubes. *Eur J Cell Biol* **55**: 209–216.
- Casar, JC, McKechnie, BA, Fallon, JR, Young, MF and Brandan, E (2004). Transient up-regulation of biglycan during skeletal muscle regeneration: delayed fiber growth along with decorin increase in biglycan-deficient mice. *Dev Biol* **268**: 358–371.
- Yoshida, N, Yoshida, S, Koishi, K, Masuda, K and Nabeshima, Y (1998). Cell heterogeneity upon myogenic differentiation: down-regulation of MyoD and Myf-5 generates 'reserve cells'. *J Cell Sci* **111**: 769–779.
- Li, Y, Cummins, J and Huard, J (2001). Muscle injury and repair. *Curr Opin Orthop* **12**: 409–415.
- Fukushima, K, Badlani, N, Usas, A, Riano, F, Fu, F and Huard, J (2001). The use of an antifibrosis agent to improve muscle recovery after laceration. *Am J Sports Med* **29**: 394–402.
- Harper, JR, Spiro, RC, Gaarde, WA, Tamura, RN, Pierschbacher, MD, Noble, NA *et al.* (1994). Role of transforming growth factor beta and decorin in controlling fibrosis. *Methods Enzymol* **245**: 241–254.
- Isaka, Y, Brees, DK, Ikegaya, K, Kaneda, Y, Imai, E, Noble, NA *et al.* (1996). Gene therapy by skeletal muscle expression of decorin prevents fibrotic disease in rat kidney. *Nat Med* **2**: 418–423.
- Kobayashi, E, Sasamura, H, Mifune, M, Shimizu-Hirota, R, Kuroda, M, Hayashi, M *et al.* (2003). Hepatocyte growth factor regulates proteoglycan synthesis in interstitial fibroblasts. *Kidney Int* **64**: 1179–1188.
- Csordas, G, Santra, M, Reed, CC, Eichstetter, I, McQuillan, DJ, Gross, D *et al.* (2000). Sustained down-regulation of the epidermal growth factor receptor by decorin. A mechanism for controlling tumor growth *in vivo*. *J Biol Chem* **275**: 32879–32887.
- Iozzo, RV, Moscatello, DK, McQuillan, DJ and Eichstetter, I (1999). Decorin is a biological ligand for the epidermal growth factor receptor. *J Biol Chem* **274**: 4489–4492.
- Schönherr, E, Sunderkotter, C, Iozzo, RV and Schaefer, L (2005). Decorin, a novel player in the insulin-like growth factor system. *J Biol Chem* **280**: 15767–15772.
- De Luca, A, Santra, M, Baldi, A, Giordano, A and Iozzo, RV (1996). Decorin-induced growth suppression is associated with up-regulation of p21, an inhibitor of cyclin-dependent kinases. *J Biol Chem* **271**: 18961–18965.
- Schönherr, E, Levkau, B, Schaefer, L, Kresse, H and Walsh, K (2001). Decorin-mediated signal transduction in endothelial cells. Involvement of Akt/protein kinase B in up-regulation of p21(WAF1/CIP1) but not p27(KIP1). *J Biol Chem* **276**: 40687–40692.
- Budas-Rwiderska, M, Jank, M and Motyl, T (2005). Transforming growth factor-beta1 upregulates myostatin expression in mouse C2C12 myoblasts. *J Physiol Pharmacol* **56** (suppl. 3): 195–214.
- Amthor, H, Nicholas, G, McKinnell, I, Kemp, CF, Sharma, M, Kambadur, R *et al.* (2004). Follistatin complexes Myostatin and antagonises Myostatin-mediated inhibition of myogenesis. *Dev Biol* **270**: 19–30.
- Lee, SJ and McPherron, AC (2001). Regulation of myostatin activity and muscle growth. *Proc Natl Acad Sci USA* **98**: 9306–9311.
- Miura, T, Kishioka, Y, Wakamatsu, J, Hattori, A, Hennebry, A, Berry, CJ *et al.* (2006). Decorin binds myostatin and modulates its activity to muscle cells. *Biochem Biophys Res Commun* **340**: 675–680.
- McCroskery, S, Thomas, M, Platt, L, Hennebry, A, Nishimura, T, McLeay, L *et al.* (2005). Improved muscle healing through enhanced regeneration and reduced fibrosis in myostatin-null mice. *J Cell Sci* **118**: 3531–3541.
- Duguez, S, Feasson, L, Denis, C and Freyssen, D (2002). Mitochondrial biogenesis during skeletal muscle regeneration. *Am J Physiol Endocrinol Metab* **282**: E802–E809.
- Lin, J, Wu, H, Tarr, PT, Zhang, CY, Wu, Z, Boss, O *et al.* (2002). Transcriptional co-activator PGC-1 alpha drives the formation of slow-twitch muscle fibres. *Nature* **418**: 797–801.
- Li, Y, Foster, W, Deasy, BM, Chan, Y, Prisk, V, Tang, Y *et al.* (2004). Transforming Growth Factor-beta1 Induces the Differentiation of Myogenic Cells into Fibrotic Cells in Injured Skeletal Muscle: A Key Event in Muscle Fibrogenesis. *Am J Pathol* **164**: 1007–1019.
- Li, Y and Huard, J (2002). Differentiation of muscle-derived cells into myofibroblasts in injured skeletal muscle. *Am J Pathol* **161**: 895–907.
- Chan, YS, Li, Y, Foster, W, Fu, FH and Huard, J (2005). The use of suramin, an antifibrotic agent, to improve muscle recovery after strain injury. *Am J Sports Med* **33**: 43–51.
- Chan, YS, Li, Y, Foster, W, Horaguchi, T, Somogyi, G, Fu, FH *et al.* (2003). Antifibrotic effects of suramin in injured skeletal muscle after laceration. *J Appl Physiol* **95**: 771–780.
- Sato, K, Li, Y, Foster, W, Fukushima, K, Badlani, N, Adachi, N *et al.* (2003). Improvement of muscle healing through enhancement of muscle regeneration and prevention of fibrosis. *Muscle Nerve* **28**: 365–372.
- Huard, J, Li, Y and Fu, FH (2002). Muscle injuries and repair: current trends in research. *J Bone Joint Surg Am* **84-A**: 822–832.
- Engert, JC, Berglund, EB and Rosenthal, N (1996). Proliferation precedes differentiation in IGF-I-stimulated myogenesis. *J Cell Biol* **135**: 431–440.
- McFarland, DC, Pesall, JE and Glickerson, KK (1993). The influence of growth factors on turkey embryonic myoblasts and satellite cells *in vitro*. *Gen Comp Endocrinol* **89**: 415–424.
- Sheehan, SM and Allen, RE (1999). Skeletal muscle satellite cell proliferation in response to members of the fibroblast growth factor family and hepatocyte growth factor. *J Cell Physiol* **181**: 499–506.
- Tatsumi, R, Anderson, JE, Nevoret, CJ, Halevy, O and Allen, RE (1998). HGF/SF is present in normal adult skeletal muscle and is capable of activating satellite cells. *Dev Biol* **194**: 114–128.
- Beauchamp, JR, Heslop, L, Yu, DS, Tajbakhsh, S, Kelly, RG, Wernig, A *et al.* (2000). Expression of CD34 and Myf5 defines the majority of quiescent adult skeletal muscle satellite cells. *J Cell Biol* **151**: 1221–1234.
- Chambers, RL and McDermott, JC (1996). Molecular basis of skeletal muscle regeneration. *Can J Appl Physiol* **21**: 155–184.
- Bischoff, R (1994). The satellite cell and muscle regeneration. In Engel, AG and Franzini-Armstrong, C (eds). *Myology: Basic and Clinical*. McGraw-Hill, New York. pp. 97–118.
- Shen, W, Li, Y, Tang, Y, Cummins, J and Huard, J (2005). NS-398, a cyclooxygenase-2-specific inhibitor, delays skeletal muscle healing by decreasing regeneration and promoting fibrosis. *Am J Pathol* **167**: 1105–1117.
- Jarvinen, TA, Jarvinen, TL, Kaariainen, M, Kalimo, H and Jarvinen, M (2005). Muscle injuries: biology and treatment. *Am J Sports Med* **33**: 745–764.
- Branton, MH and Kopp, JB (1999). TGF-beta and fibrosis. *Microbes Infect* **1**: 1349–1365.
- Franklin, TJ (1997). Therapeutic approaches to organ fibrosis. *Int J Biochem Cell Biol* **29**: 79–89.
- Zhao, J, Sime, PJ, Bringas, P, Gaudie, J and Warburton, D (1999). Adenovirus-mediated decorin gene transfer prevents TGF-beta-induced inhibition of lung morphogenesis. *Am J Physiol* **277**: L412–L422.
- Gong, R, Rifai, A, Tolbert, EM, Centracchio, JN and Dworkin, LD (2003). Hepatocyte growth factor modulates matrix metalloproteinases and plasminogen activator/plasmin proteolytic pathways in progressive renal interstitial fibrosis. *J Am Soc Nephrol* **14**: 3047–3060.
- Taniyama, Y, Morishita, R, Nakagami, H, Moriguchi, A, Sakonjo, H, Shokei, K *et al.* (2000). Potential contribution of a novel antifibrotic factor, hepatocyte growth factor, to prevention of myocardial fibrosis by angiotensin II blockade in cardiomyopathic hamsters. *Circulation* **102**: 246–252.
- Yang, J, Dai, C and Liu, Y (2002). Hepatocyte growth factor gene therapy and angiotensin II blockade synergistically attenuate renal interstitial fibrosis in mice. *J Am Soc Nephrol* **13**: 2464–2477.
- Norrbom, J, Sundberg, CJ, Ameln, H, Kraus, WE, Jansson, E and Gustafsson, T (2004). PGC-1 alpha mRNA expression is influenced by metabolic perturbation in exercising human skeletal muscle. *J Appl Physiol* **96**: 189–194.
- Xiao, X, Li, J and Samulski, RJ (1998). Production of high-titer recombinant adenovirus-associated virus vectors in the absence of helper adenovirus. *J Virol* **72**: 2224–2232.



# Relationships between Transforming Growth Factor- $\beta$ 1, Myostatin, and Decorin

## IMPLICATIONS FOR SKELETAL MUSCLE FIBROSIS\*

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Recent studies have shown that myostatin, first identified as a negative regulator of skeletal muscle growth, may also be involved in the formation of fibrosis within skeletal muscle. In this study, we further explored the potential role of myostatin in skeletal muscle fibrosis, as well as its interaction with both transforming growth factor- $\beta$ 1 and decorin. We discovered that myostatin stimulated fibroblast proliferation *in vitro* and induced its differentiation into myofibroblasts. We further found that transforming growth factor- $\beta$ 1 stimulated myostatin expression, and conversely, myostatin stimulated transforming growth factor- $\beta$ 1 secretion in C2C12 myoblasts. Decorin, a small leucine-rich proteoglycan, was found to neutralize the effects of myostatin in both fibroblasts and myoblasts. Moreover, decorin up-regulated the expression of follistatin, an antagonist of myostatin. The results of *in vivo* experiments showed that myostatin knock-out mice developed significantly less fibrosis and displayed better skeletal muscle regeneration when compared with wild-type mice at 2 and 4 weeks following gastrocnemius muscle laceration injury. In wild-type mice, we found that transforming growth factor- $\beta$ 1 and myostatin co-localize in myofibers in the early stages of injury. Recombinant myostatin protein stimulated myofibers to express transforming growth factor- $\beta$ 1 in skeletal muscles at early time points following injection. In summary, these findings define a fibrogenic property of myostatin and suggest the existence of co-regulatory relationships between transforming growth factor- $\beta$ 1, myostatin, and decorin.

Skeletal muscle injuries are one of the most common injuries encountered in sports, accounting for 10–55% of all sports

related injuries (1–3). Despite their clinical significance, current treatments remain conservative, such as the RICE principle (rest, ice, compression, and elevation) and non-steroidal anti-inflammatory drugs. However, increasing evidence shows that the administration of non-steroidal anti-inflammatory drugs decreases regeneration and increases fibrosis by inhibiting inflammation (4–8). Although injured skeletal muscle can spontaneously undergo regeneration, muscle regeneration must compete with the ensuing formation of fibrosis, especially in acute injuries (9–11). The resulting excessive fibrotic tissue might form a dense mechanical barrier that prevents the regenerating muscle fibers from maturing (12, 13), thereby resulting in incomplete skeletal muscle healing (14, 15). Researchers have widely accepted that transforming growth factor- $\beta$ 1 (TGF- $\beta$ 1)<sup>3</sup> is a potent stimulator of fibrosis in various tissues (16–19) and is closely associated with skeletal muscle fibrosis as well (20). TGF- $\beta$ 1 levels are elevated in both dystrophic muscles and injured muscles (21, 22). Researchers have also shown that TGF- $\beta$ 1 effectively induces myofibroblastic differentiation of fibroblasts both *in vitro* and *in vivo* (23, 24). The resulting overgrowth of myofibroblasts is responsible for the ensuing excessive accumulation of fibrotic tissue (23, 24). We have previously reported that TGF- $\beta$ 1 plays a significant role in both the initiation of fibrosis and the induction of myofibroblastic differentiation of myogenic cells in injured skeletal muscle (20, 25). Additionally, we have shown that antifibrosis therapies, such as interferon- $\gamma$  (INF- $\gamma$ ), suramin, relaxin, and decorin (DCN), improve the healing of injured muscle both histologically and physiologically by blocking the activity of TGF- $\beta$ 1 (26–32). However, it is unclear whether TGF- $\beta$ 1 acts alone or requires interaction with other molecules during the development of muscle fibrosis. Indeed, recent studies have shown that

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<sup>3</sup> The abbreviations used are: TGF- $\beta$ 1, transforming growth factor- $\beta$ 1; MSTN, myostatin; INF, interferon; DCN, decorin; MSTN<sup>-/-</sup>, myostatin knockout; MSTN<sup>-/-</sup>/mdx mice, mdx mice with myostatin gene knockout; GM, gastrocnemius muscle; PM, proliferation medium; DM, differentiation medium; HS, horse serum; PP1 cells, a population of preplated cells;  $\alpha$ -SMA,  $\alpha$ -smooth muscle actin; FN, fibronectin; MTT, 3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide; ELISA, enzyme-linked immunosorbent assay; PBS, phosphate-buffered saline; WT, wide-type; M.O.M., Mouse on Mouse; ECM, extracellular matrix; MRF, muscle regulatory factor; LTP, long-term proliferating; FLST, follistatin; Q-RT-PCR, quantitative reverse transcription-PCR; T $\beta$ RII, TGF- $\beta$ 1 receptor type II.

myostatin (MSTN), a member of the TGF- $\beta$  superfamily, may also be involved in fibrosis formation within skeletal muscle (33), although a direct link between MSTN and fibrosis has yet to be identified.

MSTN was initially identified as a negative regulator of muscle development (34), but unlike the ubiquitous expression of TGF- $\beta$ 1, MSTN is predominately expressed in skeletal muscle. MSTN knock-out (MSTN<sup>-/-</sup>) mice, as well as cattle and humans with a naturally occurring MSTN gene mutation, are characterized by a dramatic and widespread increase in skeletal muscle mass (34–36). Interestingly, recent reports suggest that *mdx* mice (an animal model for Duchenne muscular dystrophy) in which expression of the MSTN gene has been ablated (MSTN<sup>-/-</sup>/*mdx*) not only showed better skeletal muscle regeneration but also exhibited decreased fibrosis when compared with *mdx* mice (MSTN<sup>+/+</sup>/*mdx*) (33). These results strongly suggest that MSTN plays an important role in muscle fibrosis. To investigate this possibility, we evaluated the effect of MSTN on fibrosis formation in injured skeletal muscle. Because TGF- $\beta$ 1 plays a major role in the formation of fibrosis, we hypothesized that a relationship between TGF- $\beta$ 1 and MSTN exists. Because DCN has been shown to strongly inhibit fibrosis formation in various tissues via blocking of TGF- $\beta$ 1 activity (26, 27, 37–40), we investigated the potential for DCN to inhibit the activity of MSTN as it does for TGF- $\beta$ 1. Our findings demonstrated that MSTN is involved with fibrosis formation and interacts with TGF- $\beta$ 1 and that DCN has the ability to counteract the action of MSTN. These results contribute to a better understanding of the mechanism of skeletal muscle healing and indicate that MSTN represents a potential pharmacological target for anti-fibrogenic therapy.

## EXPERIMENTAL PROCEDURES

**Isolation of Fibroblasts from Skeletal Muscle**—The preplate technique was used to isolate fibroblasts from skeletal muscle (41). Collagen-coated flasks were used in the isolation process, because fibroblasts adhere more readily to collagen than myoblasts. After 6-week-old female C57BL/6J mice were sacrificed, their gastrocnemius muscles (GMs) were removed and minced into a coarse slurry. The muscle slurry was digested with 0.2% collagenase (type XI) for 1 h, followed by a dispase digestion (grade II, 240 ml) for 30 min, followed by a 0.1% trypsin digestion for a final 30 min at 37 °C. The extracted muscle cells were resuspended in proliferation medium (PM) consisting of Dulbecco's modified Eagle's medium (Invitrogen), 10% horse serum (HS, Invitrogen), 10% fetal bovine serum (Invitrogen), 1% penicillin/streptomycin (Invitrogen), and 0.5% chicken embryo extract (Accurate Chemical & Scientific Corp., Westbury, NY) and plated onto collagen-coated flasks. A population of preplated cells (PP1), consisting of mostly fibroblasts that attached within the first 2 h, was collected and used, in these experiments, as skeletal muscle-derived fibroblasts. This preplate technique was also used to isolate long-term proliferating (LTP) cells (muscle-derived stem cell-like cells) from WT and MSTN<sup>-/-</sup> muscle (41). Two hours after the initial plating, most of the rapidly adhering fibroblasts attached; the remaining non-adherent cells were transferred to a new collagen-coated flask every 24 h. As this process was repeated, the subsequent popu-

lations of late-adhering cells were identified as PP2, PP3, PP4, and PP5 in sequence. Following the collection of PP5, the rest of the cell suspension was incubated for an additional 72 h to allow the cells to attach in another collagen-coated flask. The final adherent cells are LTP cells (41).

**Cell Culture**—The NIH3T3 fibroblast cell line and the C2C12 myoblast cell line were purchased from the American Type Culture Collection (Manassas, VA). The cell lines or isolated PP1 fibroblasts were maintained in PM consisting of Dulbecco's modified Eagle's medium, 10% fetal bovine serum, and 1% penicillin/streptomycin until further needed. PP1 fibroblasts were plated onto collagen-coated 96-well plates for cell-proliferation analysis and onto 6-well plates for the evaluation of  $\alpha$ -smooth muscle actin ( $\alpha$ -SMA), fibronectin (FN), collagen (types I $\alpha$ 1, II $\alpha$ 2, and III $\alpha$ 1), and MSTN expression. Following an overnight incubation, PM was replaced with serum-free medium supplemented with a serum replacement (Sigma) consisting of heat-treated bovine serum albumin, heat-treated bovine transferrin, and bovine insulin. This serum replacement does not contain growth factors, steroid hormones, glucocorticoids, or cell adhesion factors. We further supplemented this media with varying concentrations of recombinant human MSTN (Leinco Technologies, Inc., St. Louis, MO) for proliferation assays (0, 100, 500, or 1000 ng/ml) and for Western blot analysis (0, 100, or 500 ng/ml). After incubation for 48 h, an MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) cell proliferation assay kit (Roche Diagnostics, Germany) was used to measure cell proliferation ( $n = 6$ ) following the instructions from the manufacturer. Western blot analysis was used to examine  $\alpha$ -SMA, FN, and MSTN expression. Some of the above procedures were repeated using NIH3T3 fibroblasts to confirm the effect of MSTN on fibroblasts.

C2C12 myoblasts, a widely used myogenic cell line (42–44), were used to examine whether DCN neutralized the inhibitory effect of MSTN on cell differentiation. We seeded C2C12 myoblasts in 12-well plates in PM at a density of 10,000 cells/well. Following an overnight incubation, PM was replaced with fresh differentiation medium (DM) containing Dulbecco's modified Eagle's medium, 2% HS, and 1% penicillin/streptomycin. We maintained a total of four sets of cultured cells. The control set received only DM, whereas the other sets received DCN alone or 1  $\mu$ g/ml MSTN combined with 0–50  $\mu$ g/ml DCN ( $n = 3$ ). Cells were cultured for 5 more days during which DM, MSTN, and DCN were changed every other day. Following a similar procedure, we examined whether recombinant follistatin (FLST) protein stimulated myogenic differentiation of C2C12 myoblasts ( $n = 3$ ), and whether soluble TGF- $\beta$ 1 receptor type II (T $\beta$ RII, 100 and 1000 ng/ml, R&D Systems, Inc., Minneapolis, MN) was able to attenuate MSTN-inhibited myoblast differentiation ( $n = 3$ ).

**Western Blot Analysis**—After culturing, the cells were lysed with T-PER<sup>®</sup> Tissue Protein Extraction Reagent with the addition of protease inhibitors (Pierce). Equal amounts of cellular protein were loaded into each well and separated by 10% SDS-PAGE. Nitrocellulose membrane blotting was performed under standard conditions. The following primary antibodies were used for immunoblotting: mouse anti- $\beta$ -actin IgG (1:8000, Sigma), mouse anti-glyceraldehyde-3-phosphate dehydrogen-



TABLE 1

Sequence of primer set

Gene name (GenBank™ no.)	Primer pair (S: sense primer, A: anti-sense primer)	PCR products
Procollagen type I $\alpha$ 1 (BC050014)	S: 5'-GAAGAACTGGACTGTCCCAAC-3' A: 5'-CCTCGACTCCTACATCTTCTG-3'	bp 103
Procollagen type I $\alpha$ 2 (AK075707)	S: 5'-TCTGGTAAAGAAGGCCCTGTG-3' A: 5'-GTCCAGGGAATCCGATGTTG-3'	106
Procollagen type III $\alpha$ 1 (AK041115)	S: 5'-AGGCTGAAGGAAACAGCAAA-3' (45) A: 5'-TAGTCTCATTGCCTTGCCTG-3'	116
TGF- $\beta$ 1 (BC 013738)	S: 5'-CTAATGGTGGACCGCAACAAC-3' A: 5'-CACTGCTTCCCGAATGTCTGA-3'	99
18 S rRNA (?) <sup>a</sup>		N/A

<sup>a</sup> Sequences of the primer pairs for 18 S rRNA not provided by Applied Biosystems Inc. for proprietary reasons.

ase IgG (1:5000, Abcam Inc., Cambridge, MA), rabbit anti-MSTN IgG (1:3000, Chemicon, Temecula, CA), mouse anti- $\alpha$ -SMA IgG (1:1000, Sigma), mouse anti-FN IgG (1:3000), and rat anti-TGF- $\beta$ 1 IgG (1:1000, BD Pharmingen, San Jose, CA).

**Quantitative RT-PCR**—Quantitative RT-PCR (Q-RT-PCR) was used to examine the mRNA expression levels of procollagen (types I $\alpha$ 1, I $\alpha$ 2, and III $\alpha$ 1) in PP1 fibroblasts treated with MSTN (100, 200, and 500 ng/ml) for 12, 24, and 48 h. The mRNA was extracted using an RNeasy Plus kit (Qiagen). The cDNA templates for Q-RT-PCR were synthesized using a RETROscript® kit (Ambion Inc., Austin, TX). Q-RT-PCR was carried out in an ABI Prism 7000 sequence detector (Applied Biosystems Inc., Foster City, CA) with SYBR Green PCR Master Mix Reagent (Applied Biosystems) as a detector. All target gene expressions were normalized to 18 S rRNA levels. The primer pair of procollagen III $\alpha$ 1 was from a previous study (45). The primer pairs are displayed in Table 1.

**ELISA**—Enzyme-linked immunosorbent assay (ELISA) was performed to determine whether recombinant MSTN protein stimulated TGF- $\beta$ 1 secretion in C2C12 myoblasts. C2C12 myoblasts were plated into a 48-well plate and exposed to a range of MSTN concentrations from 0 to 500 ng/ml. Fresh, recombinant MSTN protein was added every 2 days. Cell supernatants were collected at 2 and 4 days ( $n = 5$ ). These supernatants were centrifuged to remove cell debris and stored at  $-80^{\circ}\text{C}$  until the ELISA was performed. The mouse/rat/porcine TGF- $\beta$ 1 immunoassay kit (R&D Systems, Inc.) was used to quantitatively measure the secreted TGF- $\beta$ 1 levels in cell culture supernatants, according to the manufacturer's protocol.

**Immunocytochemistry**—To monitor the differentiation capacity of the myogenic cells, they were fixed in cold methanol for 2 min after induction of differentiation in 12-well plates. Following a phosphate-buffered saline (PBS) wash, the cells were blocked with 10% HS (Vector Laboratories, Inc., Burlingame, CA) for 30 min, and then incubated with an anti-myosin heavy chain antibody (Sigma) in 2% HS overnight. A negative control was performed by omitting the primary antibody. The next day, after several PBS rinses, the cells were incubated with the secondary antibody goat anti-mouse IgG conjugated with Cy3 (Sigma) for 1 h. Hoechst 33258 dye was used in each experiment to stain cell nuclei. Fusion index (ratio of nuclei in myotubes to all nuclei) was calculated (%) to evaluate myogenic differentiation.

**Animal Model**—All experimental animal protocols were approved by the Animal Research and Care Committee at Children's Hospital of Pittsburgh (protocols 15-3 and 17-05).

C57BL/6 wild-type (WT) (Jackson Laboratories, Bar Harbor, ME) and MSTN<sup>-/-</sup> mice (7–8 weeks of age) were used in this study. All MSTN<sup>-/-</sup> mice used were offspring of MSTN<sup>-/-</sup> homozygotes, and PCR was used to confirm the genotype of all MSTN<sup>-/-</sup> mice. The RT-PCR test was randomly used to confirm the lack of MSTN gene transcription in MSTN<sup>-/-</sup> mice throughout the experiments. The skeletal muscle mass of MSTN<sup>-/-</sup> mice and WT mice were also compared to confirm the desired phenotype. The mice were anesthetized with isoflurane controlled under an IMPAC6 anesthetic delivery machine (VetEquip, Pleasanton, CA). Both GMs of each mouse were laterally lacerated to create an injury model as previously described (27–29). A surgical blade (no. 11) was used to make a lateral laceration through 50% of the muscle width and 100% of the muscle thickness in the area of the GM with the largest diameter. We harvested the mouse GMs at 2 and 4 weeks post-surgery. There were 6–8 mice (12–16 GMs) in the WT and MSTN<sup>-/-</sup> mouse groups for both time points. The muscles were isolated, removed, and snap-frozen in 2-methylbutane pre-cooled in liquid nitrogen. After Masson's trichrome staining (IMEB Inc., Chicago, IL), Northern Eclipse software (Empix Imaging, Inc., Cheektawaga, NY) was used to measure areas of fibrotic tissue in the injured sites. In each sample, three representative non-adjacent sections were chosen. The ratio of the fibrotic area to the cross-sectional area was used to estimate the extent of fibrosis formation. To determine the skeletal muscle's regeneration efficiency, minor axis diameters (the smallest diameter) of regenerating muscle fibers were measured using Northern Eclipse software on cross-sections of GMs. The diameters of over 350 consecutively centro-nucleated myofibers were measured in each GM.

To analyze the expression of MSTN in the injured GM, 18 8-week-old female C57BL/6 WT mice underwent bilateral GM laceration. Mice were sacrificed at 1, 3, 5, 7, 10, 14, 21, and 30 days after injury ( $n = 3$  for each time point), and GMs were harvested, frozen, and stored at  $-80^{\circ}\text{C}$ .

300,000 LTP cells obtained from MSTN<sup>-/-</sup> mice were transplanted in the GMs of 3 8-week-old *mdx/scid* mice using a protocol previously described (41). The same amount of cells obtained from WT mice was injected into contralateral GMs of *mdx/scid* mice to serve as our control. Mice were sacrificed after 4 weeks, and GMs were frozen in liquid nitrogen. Immunostaining with anti-mouse dystrophin antibody (Abcam Inc.) was performed to detect dystrophin-positive myofibers that regenerated from transplanted cells.

To examine whether the injection of MSTN induced TGF- $\beta$ 1 expression, we injected MSTN (1000 ng in 10  $\mu$ l of PBS) into the non-injured GM of WT mice. Contralateral GMs were injected with 10  $\mu$ l of PBS and served as a control. Three WT mice were used at each time point. Mice injected with MSTN were sacrificed at 4, 10, 24, and 48 h after injection ( $n = 3$  for each time point). Immunohistochemical staining was performed to detect MSTN and TGF- $\beta$ 1 expression in muscle fibers.

**Immunohistochemistry**—Frozen GMs were sectioned at 10- $\mu$ m thickness, and immunohistochemical analysis was performed to detect MSTN and TGF- $\beta$ 1 expression. Tissue sections were fixed in 4% formalin for 5 min followed by two 10-min washes with PBS. The sections were then blocked with 10% HS for 1 h. The rabbit MSTN primary antibody was diluted 1:100 in 2% HS and incubated with sections overnight at 4 °C. The following day, the sections were washed three times with PBS and then incubated with the secondary antibody, goat anti-rabbit IgG conjugated with Cy3 (Sigma). The Mouse-on-Mouse immunodetection kit (M.O.M., Vector Laboratories, Inc.) was then used to stain for TGF- $\beta$ 1 following the manufacturer's protocol. The slides were incubated with M.O.M. blocking reagent for 1 h, washed with PBS, and then incubated with M.O.M. diluent for 5 min. TGF- $\beta$ 1-specific primary antibodies (Vector Laboratories, Inc.) were diluted 1:150 in the M.O.M. diluent and incubated with the slides for 30 min. After washing with PBS, the sections were incubated with anti-mouse IgG conjugated with fluorescein isothiocyanate (diluted 1:200 with M.O.M. diluent, Sigma) for 1 h. Hoechst 33258 dye was used to stain the nuclei. In a separate experiment following a similar procedure, polyclonal rabbit anti-DCN IgG (LF-113, National Institute of Dental Research, Bethesda, MD) was used to stain tissue sections of WT and MSTN<sup>-/-</sup> GMs 2 weeks after laceration.

**Statistical Analysis**—All of the results from this study are expressed as the mean  $\pm$  S.D. The differences between means were considered statistically significant if  $p < 0.05$ . The Student's  $t$  test was used to compare the difference in skeletal muscle regeneration, fibrosis formation between MSTN<sup>-/-</sup> and WT mice, and the myogenic differentiation capacity between MSTN<sup>-/-</sup> and WT LTP cells. All other data were analyzed by analysis of variance followed by post hoc Tukey's multiple comparison test. Error bars on the figures represent the  $\pm$  S.D. (\*,  $p < 0.05$ ; \*\*,  $p < 0.01$ ).

## RESULTS

**Effects of MSTN on Fibroblasts**—MTT proliferation tests showed that, after 48 h of incubation, MSTN significantly stimulated the proliferation of PP1 and NIH3T3 fibroblasts in a dose-dependent manner (Fig. 1A).  $\alpha$ -SMA, the actin isoform originally found in contractile vascular smooth muscle cells, has been the most reliable marker of myofibroblasts to date (24). Western blot analysis indicated that MSTN (100 and 200 ng/ml) increased  $\alpha$ -SMA expression in PP1 and NIH3T3 fibroblasts (Fig. 1B). Q-RT-PCR revealed that MSTN stimulated procollagen (type I $\alpha$ 1, I $\alpha$ 2, and III $\alpha$ 1) mRNA expression at 48 h (Fig. 1C). Additionally, MSTN stimulated the expression of FN

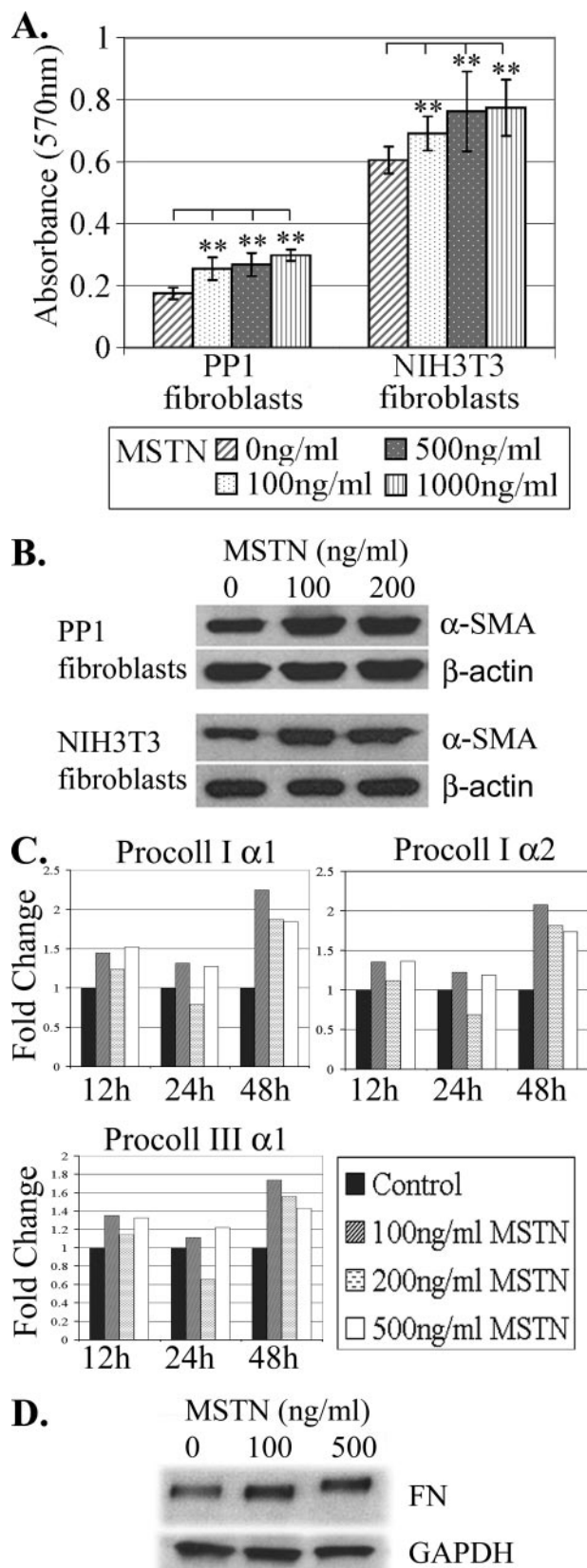
protein, a component of the extracellular matrix (ECM), in PP1 fibroblasts (Fig. 1D).

**MSTN Expression in Injured Skeletal Muscle**—After laceration injury, different time points were selected to detect MSTN expression in GMs. The degenerative and repair remodeling phases were represented by post-injury time points of 1–3 and 5–30 days following injury, respectively. Immunostaining for MSTN indicated MSTN expression within degenerative myofibers at 1 and 3 days after the injury (data not shown). On day 5, by the time a majority of newly regenerating myofibers was seen, faint MSTN signals were detected in the cytoplasm of regenerating centro-nucleated myofibers (red fluorescence and white arrowheads), whereas green collagen IV immunostaining indicates basal lamina of myofibers (Fig. 2A). MSTN expression was also observed in the nuclei of both the mononuclear cells (white arrows) and the regenerating centro-nucleated myofibers (Fig. 2A), which is especially obvious in the enlarged image (white arrowhead Fig. 2A, inset). On day 7 (Fig. 2B), a decrease in MSTN expression within most of the regenerating myofiber cytoplasm was seen (white arrowheads), whereas some myotubes without intact basal lamina were strongly stained with MSTN antibody, which is increased 14 days post-injury (white arrows, Fig. 2C). The nuclei of myofibers remained MSTN-positive (yellow arrowhead, Fig. 2, B and C, insets). MSTN staining disappeared from most regenerated myofibers 30 days after laceration (white arrowheads, Fig. 2D). Fig. 2, E, F, G, and H, depict negative controls of injured muscle at 5, 7, 14, and 30 days after laceration, respectively, where the MSTN antibody was replaced by the non-immune rabbit IgG. Collagen type IV was also stained on these samples to visualize the basal lamina.

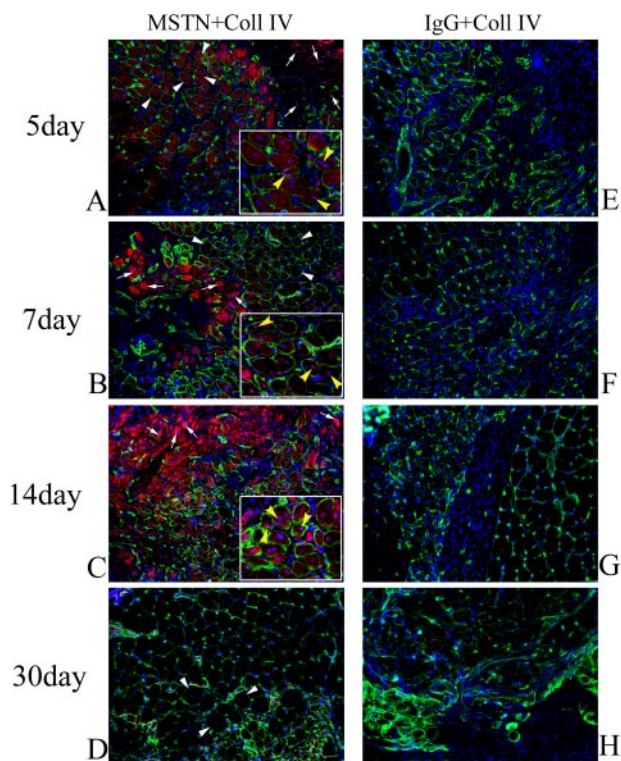
**Reduced Fibrosis and Enhanced Skeletal Muscle Regeneration in MSTN<sup>-/-</sup> Mice after Laceration**—At 2 weeks following injury, we observed extensive deposition of collagenous tissue in the WT and MSTN<sup>-/-</sup> mice (data not shown). After 4 weeks, the deepest area of the injured site was filled with regenerating myofibers of large diameter, and the fibrotic region was limited to the superficial zone of the laceration site (Fig. 3A). We observed fewer fibrotic connective tissue deposits between regenerating myofibers in the injured muscle of MSTN<sup>-/-</sup> mice compared with the prominent scar region in the injured WT mouse muscle (Fig. 3A). Quantification of fibrotic tissue (i.e. the ratio of the fibrotic area to the cross-sectional area) revealed that there was a significantly smaller fibrous area in MSTN<sup>-/-</sup> skeletal muscle as compared with WT skeletal muscle at 2 weeks ( $11.5 \pm 3.5\%$  versus  $15.3 \pm 3.1\%$ ;  $p < 0.01$ ) and at 4 weeks ( $2.1 \pm 0.4$  versus  $6.3 \pm 2.1$ ;  $p < 0.01$ ) after injury (Fig. 3B).

We used the minor axis diameter (smallest diameter) of centro-nucleated regenerating myofibers to evaluate skeletal muscle regeneration after laceration injury. At 2 weeks after GM laceration, regenerating myofibers were relatively small (data not shown). At 4 weeks, some large, mature myofibers could be observed among the small, centro-nucleated, regenerating myofibers (Fig. 3C). Quantification showed that MSTN<sup>-/-</sup>-regenerating myofibers had diameters 38.8% larger than WT myofibers ( $36.1 \pm 2.5 \mu\text{m}$  versus  $26.0 \pm 2.2 \mu\text{m}$ ,  $p < 0.01$ ) at 2 weeks after laceration, and the mean diameter of regenerating myofibers in MSTN<sup>-/-</sup> mice remained 21.1% larger than the





**FIGURE 1. MSTN stimulated fibroblast proliferation and fibrotic protein expression in fibroblasts.** A, both muscle-derived fibroblasts (PP1) and NIH3T3 fibroblasts were cultured with MSTN, varying in concentration from 0 to 1000 ng/ml for 48 h. Cell proliferation was determined by MTT assay. These results are presented as absorbance values ( $n = 6$ ) of purple formazan crystal at 570 nm, which directly correlates to the number of living cells. Fibroblasts

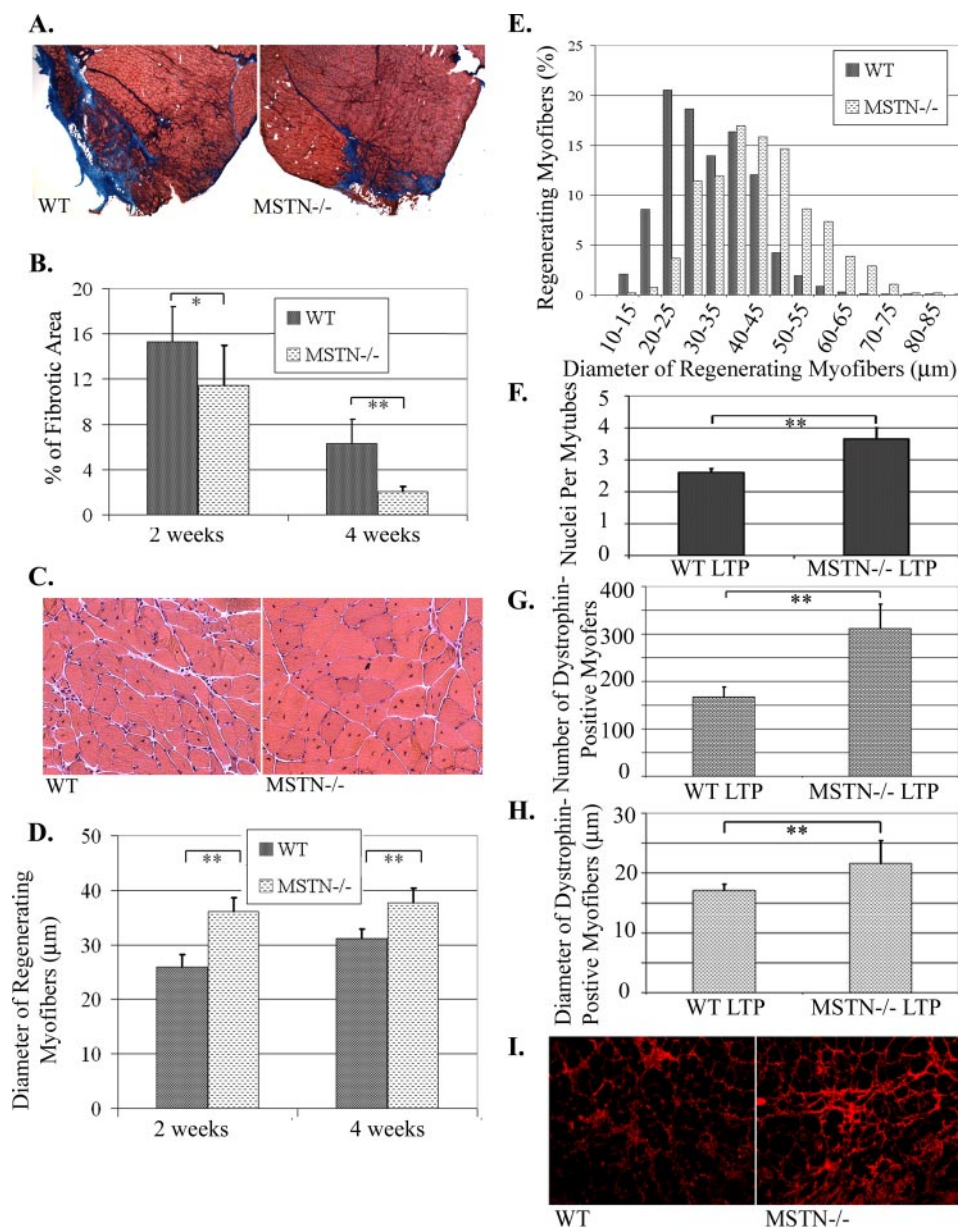


**FIGURE 2. MSTN localization in injured GMs.** A–H, GMs from WT mice were harvested at different time points after laceration injury, and frozen sections were immunostained with rabbit anti-MSTN and goat anti-collagen type IV antibodies. MSTN, collagen IV, and cell nuclei are red, green, and blue, respectively (A–D). Non-immune rabbit IgG was used as negative control for rabbit anti-MSTN antibody (E–H), but were stained with the collagen type IV antibody. A, at 5 days, faint MSTN signals could be detected in the cytoplasm of newly formed myofibers (white arrowheads) with basal lamina, and a relatively higher MSTN staining can be observed in the nuclei of regenerating myofiber (yellow arrowhead) and mononuclear cells (white arrow). B, at 7 days, MSTN staining is not evident in the cytoplasm of most regenerating myofibers (white arrowhead), whereas some of the regenerating small myotubes without basal lamina show intense MSTN staining in the cytoplasm (white arrows). Yellow arrowheads in the inset indicate positive signal in nuclei of regenerating myofibers. C, at 14 days, there were more MSTN-positive myotubes without basal lamina (white arrow). Yellow arrowheads in the inset indicate positive signal in nuclei of regenerating myofibers. D, at 30 days, most of regenerating myofibers were MSTN-negative (arrowheads). (Magnification,  $\times 200$ ; inset magnification,  $\times 400$ .)

mean diameter of regenerating myofibers in the WT mice ( $37.7 \pm 2.7 \mu\text{m}$  versus  $31.1 \pm 1.8 \mu\text{m}$ ,  $p < 0.01$ ) 4 weeks after injury (Fig. 3D). The distribution of the regenerating myofiber diameters showed that there was an increase in the percentage of larger regenerating myofibers in  $\text{MSTN}^{-/-}$  mice compared with WT mice (e.g.  $\sim 7.38\%$  of regenerating myofiber diameters in  $\text{MSTN}^{-/-}$  mice fell into a range of  $50\text{--}55 \mu\text{m}$  versus  $1.92\%$  of those in WT mice).

**Improved Myogenic Potential with  $\text{MSTN}^{-/-}$  LTP Cells—**LTP cells were isolated from WT and  $\text{MSTN}^{-/-}$  mice. When we cultivated these  $\text{MSTN}^{-/-}$  LTP cells in low serum medium, they differentiated into myotubes that were significantly larger

were cultured in DM for 2 days with the addition of various concentrations of MSTN. Expressions of different proteins were analyzed by Western blot. B, the expression of  $\alpha$ -SMA in PP1 fibroblasts or NIH3T3 fibroblast is shown. C, Q-RT-PCR analysis of procollagen (types  $\text{I}\alpha 1$ ,  $\text{I}\alpha 2$ , and  $\text{III}\alpha 1$ ) mRNA expression in PP1 fibroblasts treated with MSTN. Results are presented as the ratio against the gene expression in the control. D, expression of FN in PP1 fibroblasts after MSTN treatment (\*,  $p < 0.05$ ; \*\*,  $p < 0.01$ ).



**FIGURE 3. Inhibition of MSTN favors skeletal muscle regeneration.** A, sections from injured WT and MSTN<sup>-/-</sup> GMs were stained with Masson's trichrome-staining protocol 4 weeks after laceration to determine fibrotic tissue levels. As a result, collagenous tissue is stained blue. B, quantification of fibrotic tissue of WT versus MSTN<sup>-/-</sup> GMs 2 and 4 weeks after laceration. C, myofibers in WT and MSTN<sup>-/-</sup> GMs were visualized by hematoxylin and eosin staining 4 weeks after laceration. Regenerating myofibers were distinguished by their centralized nuclei. D, quantification of the diameters of regenerating myofibers. E, the distribution of regenerating myofiber diameters at 4 weeks after laceration injury. F, myogenic differentiation capacity of WT and MSTN<sup>-/-</sup> LTP cell *in vitro*. *In vivo*, transplantation of MSTN<sup>-/-</sup> LTP into *mdx/scid* mice led to a high number of dystrophin-positive muscle fibers when compared with WT LTP. G, the number of dystrophin-positive myofibers was counted. H, the diameter of dystrophin-positive myofibers was measured. I, increased DCN immunostaining in injured skeletal muscle of MSTN<sup>-/-</sup> mice compared with WT mice 2 weeks after laceration. DCN (red) is detected in the ECM between myofibers. (Magnifications: in C and I, ×200; in A, ×100; \*, p < 0.05; \*\*, p < 0.01.)

(more nuclei per myotube,  $n = 3$ ) than the myotubes formed by the fusion of WT LTP cells (Fig. 3F). When we injected the MSTN<sup>-/-</sup> LTP cells into the muscle of *mdx/scid* mice, they regenerated significantly more dystrophin-positive muscle fibers than did the WT LTP (Fig. 3G). These regenerating muscle fibers were also significantly larger in diameter (Fig. 3H).

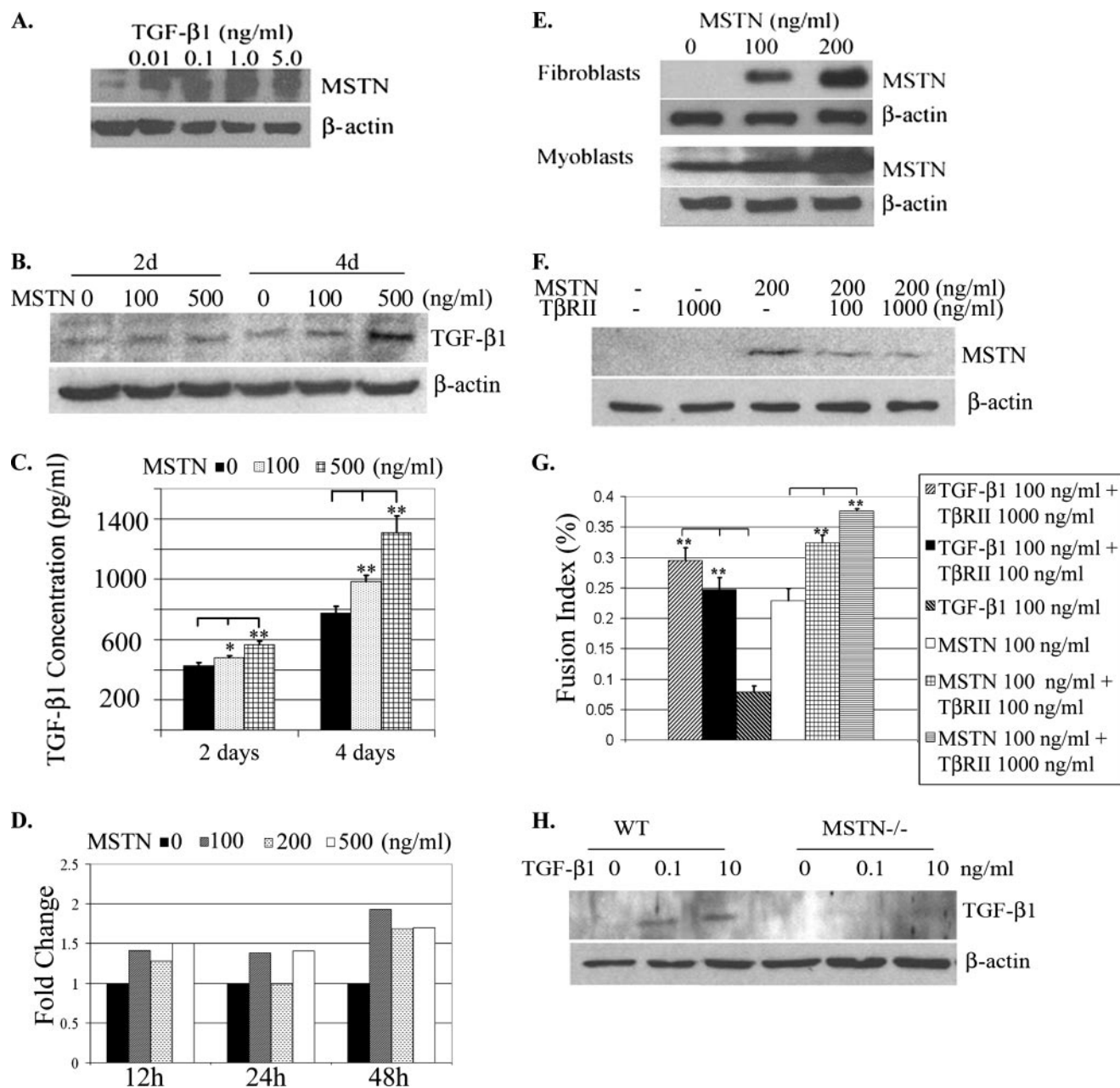
**Elevated DCN Expression in Injured MSTN<sup>-/-</sup> Mice**—To investigate the underlying mechanism for improved muscle

healing in MSTN<sup>-/-</sup> mice, we examined the expression of DCN, a molecule that has been shown to decrease fibrosis and enhance muscle regeneration (20, 27) in injured MSTN<sup>-/-</sup> skeletal muscle. Immunohistochemical staining revealed that there was more abundant DCN expression in the regenerating skeletal muscle of MSTN<sup>-/-</sup> mice than that of WT mice 2 weeks after injury (Fig. 3I). This higher level of DCN expression may be involved with the increased regeneration and decreased fibrosis observed in the injured muscle of MSTN<sup>-/-</sup> mice.

**Relationship between TGF- $\beta$ 1 and MSTN<sup>-/-</sup>**—Western blot analysis showed that the levels of MSTN in C2C12 myoblasts treated with different concentrations of TGF- $\beta$ 1 were elevated in a dose-dependent manner when compared with non-treated controls, suggesting that TGF- $\beta$ 1 stimulates MSTN expression in C2C12 myoblasts (Fig. 4A). After incubation with increasing concentrations of recombinant MSTN protein, MSTN was shown to stimulate TGF- $\beta$ 1 expression in C2C12 myoblasts (especially with the highest dose) at 4 days post-stimulation (Fig. 4B). Furthermore, ELISA showed that MSTN significantly increased TGF- $\beta$ 1 secretion by C2C12 myoblasts in a dose-dependent manner at 2 and 4 days. After 4 days of stimulation with MSTN (500 ng/ml), C2C12 myoblasts secreted ~2-fold more TGF- $\beta$ 1 as compared with control cells (Fig. 4C). Q-RT-PCR revealed that MSTN (100, 200, and 500 ng/ml) also increased TGF- $\beta$ 1 mRNA expression 48 h post-stimulation (Fig. 4D).

PP1 fibroblasts did not express detectable MSTN protein. However, after treatment with MSTN (100 and 200 ng/ml) for 48 h, PP1 fibroblasts began to express MSTN as indicated by Western blot analysis (Fig. 4E). MSTN also stimulated MSTN expression in C2C12 myoblasts (Fig. 4E). MSTN-induced MSTN autocrine expression in PP1 fibroblasts is reduced by soluble T $\beta$ RII, which blocks the TGF- $\beta$ 1 signaling pathway (Fig. 4F). Moreover, our results indicated that soluble T $\beta$ RII was also able to restore MSTN-inhibited C2C12 myoblast differentiation (Fig. 4G). We also examined whether exogenous



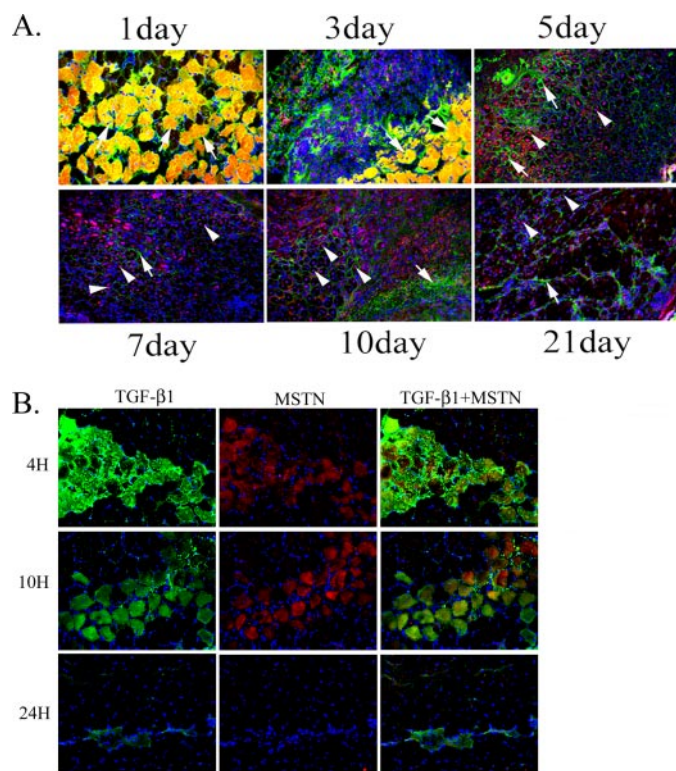


**FIGURE 4. The relationship between TGF- $\beta$ 1 and MSTN *in vitro*.** *A*, Western blot analysis of MSTN expression in C2C12 myoblasts treated with different concentrations of TGF- $\beta$ 1 ranging from 0 to 5.0 ng/ml for 48 h. *B*, C2C12 myoblasts were treated with different concentrations of MSTN in DM. Cell lysates were collected at 2 and 4 days to examine TGF- $\beta$ 1 expression by Western blot; *C*, while the conditioned medium was collected at the same time points, the levels of TGF- $\beta$ 1 in the medium were also analyzed by ELISA. *D*, Q-RT-PCR for TGF- $\beta$ 1 after MSTN treatment (100, 200, and 500 ng/ml) in PP1 fibroblasts. *E*, the level of MSTN expression in PP1 fibroblasts and C2C12 myoblasts treated with MSTN recombinant protein. *F*, Western blots were used to determine MSTN expression level in PP1 fibroblasts after cells were treated with either MSTN or both MSTN and soluble T $\beta$ RII for 48 h. *G*, C2C12 myoblasts were cultured in DM with different treatments, TGF- $\beta$ 1, MSTN, TGF- $\beta$ 1 and T $\beta$ RII, or MSTN and T $\beta$ RII, for 4 days. Fusion indexes were used to access impacts of treatments on C2C12 myoblast differentiation. *H*, myoblasts isolated from WT, and MSTN $^{-/-}$  GMs were grown for 48 h under stimulation by TGF- $\beta$ 1. Western blot analysis was used to detect TGF- $\beta$ 1 expression in WT and MSTN $^{-/-}$  cells (\*,  $p < 0.05$ ; \*\*,  $p < 0.01$ ).

TGF- $\beta$ 1 recombinant protein was able to stimulate autocrine expression of TGF- $\beta$ 1 in MSTN $^{-/-}$  muscle cells as it does in C2C12 myoblasts (20). We observed that exogenous TGF- $\beta$ 1 could induce its autocrine expression in WT primary myoblasts but not on primary MSTN $^{-/-}$  myoblasts (Fig. 4H).

*In vivo*, We observed co-expression of TGF- $\beta$ 1 (green) and MSTN (red) in degenerative myofibers 1 and 3 days after laceration injury (white arrow, Fig. 5A). By day 5, MSTN was

detected mainly in the nuclei of the regenerating myofibers (white arrowhead) with the exception of a few MSTN-positive necrotic myofibers, whereas TGF- $\beta$ 1 was present in the surrounding ECM (white arrow). MSTN was still detected in the nuclei of regenerating myofibers 21 days after injury (white arrow, Fig. 5A). The injection of MSTN into non-injured GMs induced TGF- $\beta$ 1 expression in the myofibers at 4, 10, and 24 h after injection. As shown in Fig. 5B, MSTN (red) and TGF- $\beta$ 1 (green) were co-expressed in myofibers at



**FIGURE 5. The relationship between TGF- $\beta$ 1 and MSTN *in vivo*.** A, both GMs of each adult WT mouse underwent laceration injury. Mice GMs were harvested at the indicated times. Double staining of TGF- $\beta$ 1 (green) and MSTN (red) was performed. In the 1- and 3-day images, a white arrow indicates degenerative myofibers. At all other time points, the white arrow and arrowhead indicate ECM and nuclei of myofibers, respectively. B, co-localization of TGF- $\beta$ 1 and MSTN in myofibers after recombinant MSTN protein injection. We injected 1000 ng of MSTN protein in 10  $\mu$ l of PBS into GMs of WT mice. Mice were sacrificed at different time points after injection. Frozen sections of GMs were double-stained with anti-TGF- $\beta$ 1 and anti-MSTN antibodies (magnification,  $\times 200$ ).

4 and 10 h. After 24 h, MSTN disappeared, and only a few TGF- $\beta$ 1-positive myofibers could be observed.

**DCN Counteracts the Effect of MSTN**—As previously shown in Fig. 1A, 0.1  $\mu$ g/ml MSTN significantly stimulated PP1 fibroblast proliferation. This dosage was selected to examine whether DCN could reduce the proliferative influence of MSTN on PP1 fibroblasts. After PP1 fibroblasts were incubated with MSTN and exposed to varying concentrations of DCN for 48 h, MTT assay revealed that the addition of DCN significantly repressed the stimulatory effect of MSTN on PP1 proliferation in a dose-dependent manner as expected (Fig. 6A). These findings are comparable to a previous report showing that DCN blocked the stimulatory effect of TGF- $\beta$ 1 on PP1 fibroblasts (27).

Our earlier results indicated that MSTN induced its own expression, in an autocrine manner, in PP1 fibroblasts (Fig. 4E). Therefore, we examined the ability of DCN to block the MSTN autocrine expression in PP1 fibroblasts. As previously shown, PP1 fibroblasts that were not treated with MSTN failed to express detectable MSTN protein, whereas PP1 fibroblasts treated with MSTN showed a high level of MSTN expression in comparison to the control (Figs. 4E and 6B). However, DCN decreased MSTN autocrine expression by PP1 fibroblasts in a dose-dependent manner (Fig. 6B).

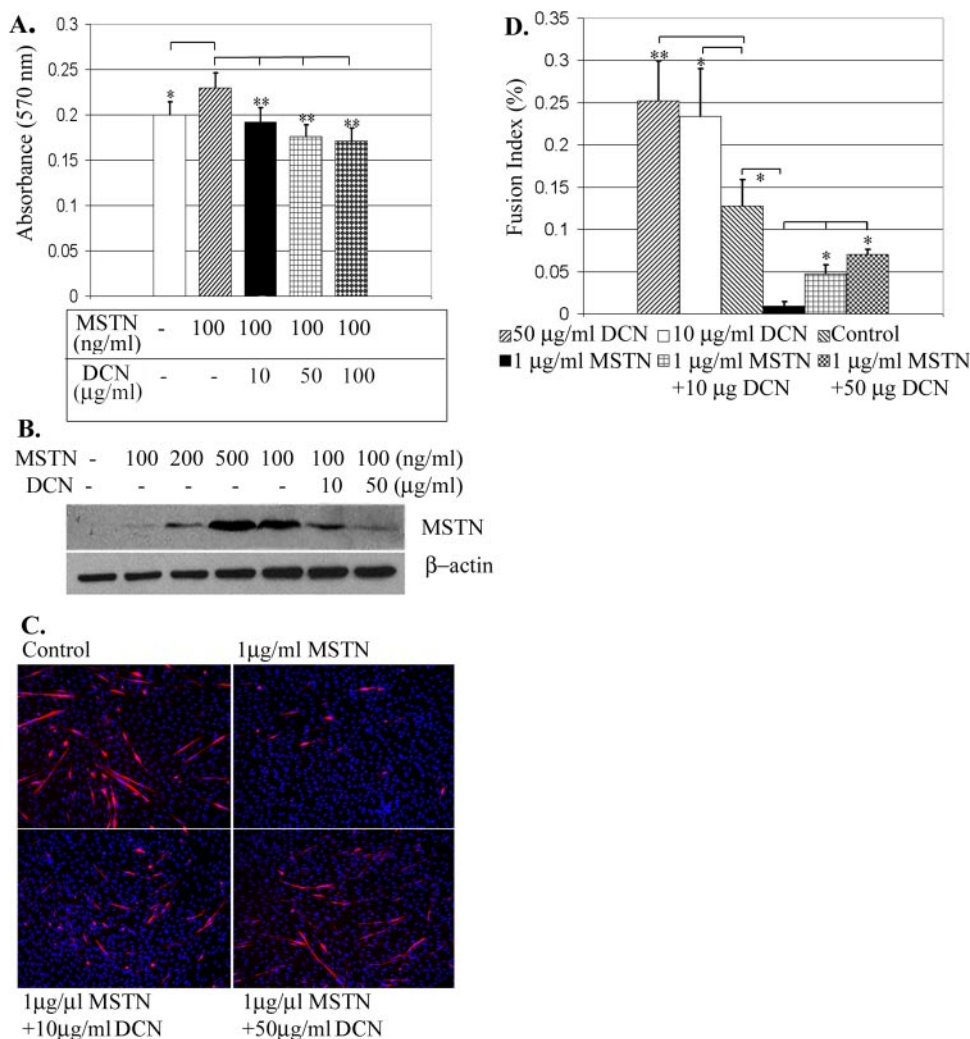
Our previous experiments showed that 1  $\mu$ g/ml MSTN almost completely inhibited myoblast differentiation (data not shown). Therefore, we chose this dose to assess whether DCN treatment could reverse MSTN-inhibited myogenic differentiation in C2C12 cells. Except for the control cells, the cultures were treated with DCN alone or 1  $\mu$ g/ml MSTN combined with increasing concentrations of DCN (0–50  $\mu$ g/ml). Following a 5-day incubation, DCN-treated groups (data not shown) and controls showed widespread myosin heavy chain-positive myotubes, whereas cells treated with MSTN alone contained only a few myotubes (Fig. 6C). The addition of DCN reversed the inhibition of MSTN on myogenic differentiation, as indicated by the increase in the number and size of myotubes in comparison to the MSTN-treated group (Fig. 6C). Measurements showed that DCN treatment promoted C2C12 myoblast differentiation by significantly increasing fusion indexes in a dose-dependent manner (Fig. 6D), suggesting that DCN attenuated the inhibitory effect of MSTN and, thereby, stimulated myoblast fusion.

**Inhibitory Effects of DCN on MSTN May Be Mediated by FLST**—To further explore whether DCN regulated MSTN activity via an intermediate molecule, we investigated the effect of DCN on the expression of FLST, which is able to bind to MSTN and suppress its activity (46). We found an up-regulation of FLST expression by C2C12 myoblasts 48 and 72 h after addition of 10  $\mu$ g/ml DCN (Fig. 7A). Our results also revealed the ability of FLST to stimulate myogenic differentiation, which was demonstrated by the presence of larger myotubes containing more nuclei in comparison to the control group (Fig. 7B). In a dose-dependent manner, FLST treatment led to a significant increase in fusion index (Fig. 7C) compared with the control group, suggesting that FLST promotes myogenic differentiation and accelerates the maturation of myotubes.

## DISCUSSION

MSTN has been drawing more and more attention due to mounting evidence indicating that inhibition of MSTN significantly improves skeletal muscle diseases such as muscle dystrophy. But, the role of MSTN in injured skeletal muscle and its relationships with other molecules such as TGF- $\beta$ 1 and DCN (important key factors in muscle healing) remain unknown. Recent studies reported by Yamanouchi *et al.* (47) highlight the expression of MSTN in fibroblasts in injured skeletal muscle, suggesting that fibroblasts may be a source of MSTN. Previously, we have shown that TGF- $\beta$ 1 significantly promotes proliferation of PP1 fibroblasts (27). Here, our *in vitro* study shows that MSTN activates fibroblasts by stimulating fibroblast proliferation and inducing their expression of  $\alpha$ -SMA analogous to that of TGF- $\beta$ 1. Like TGF- $\beta$ 1 (48), MSTN may transiently attract fibroblasts into an injury site, further inducing them to express MSTN in an autocrine fashion; they then differentiate into myofibroblasts, thereby accelerating the deposition of the ECM. Researchers widely believe that prolonged presence and excessive activity of myofibroblasts is associated with the abnormal accumulation of ECM components in injured and diseased tissue (49, 50). Moreover, MSTN has been shown to induce procollagen (types I $\alpha$ 1, I $\alpha$ 2, and III $\alpha$ 1), mRNA, and FN protein expression in PP1 fibroblasts. McCroskery *et al.* (51) recently confirmed the correlation of MSTN expression to the





**FIGURE 6. DCN blocks the effects of MSTN on PP1 fibroblasts and C2C12 myoblasts.** A, PP1 fibroblasts were treated for 48 h with 100 ng/ml MSTN or combinations of MSTN and DCN. Non-treated cell cultures were used as a control. MTT assay was performed to assess cell proliferation. B, after incubation of PP1 fibroblasts with MSTN, or a combination of MSTN and DCN, Western blot analysis was performed to determine whether DCN reduced the autocrine expression of MSTN in PP1 fibroblasts stimulated with MSTN. C, C2C12 myoblasts were cultured without treatment, with 1 μg/ml MSTN alone, or co-incubated with 1 μg/ml MSTN and different concentrations of DCN for 5 days. Myotubes were monitored by anti-skeletal myosin heavy chain immunostaining; nuclei were stained by Hoechst 33258 (magnification,  $\times 100$ ). D, fusion indexes were determined to estimate the differentiation capacity of C2C12 myoblasts in response to different treatments.

formation of fibrosis by showing less fibrosis formation in the notoxin-damaged tibialis anterior muscle in MSTN $^{-/-}$  mice 4 weeks after injury as compared with WT mice. Given the results collected in our *in vitro* study, we hypothesized that a lack of MSTN in knock-out mice would decrease the proliferation of fibroblasts and reduce their production of collagenous tissue in injured skeletal muscle. This was made evident by a significant decrease in the formation of fibrosis in MSTN $^{-/-}$  mice at 2 and 4 weeks after injury when compared with WT mice. Moreover, we found an elevated expression level of DCN, an inhibitor of TGF- $\beta$ 1, in injured MSTN $^{-/-}$  skeletal muscles compared with injured WT muscles at 2 weeks after injury. In accordance with this result, increased DCN mRNA has been observed in regenerating MSTN $^{-/-}$  muscle (51). Increased DCN might inhibit the effect of TGF- $\beta$ 1, thereby partially explaining the reduced fibrosis and enhanced regeneration in injured MSTN $^{-/-}$  muscle. To understand the mechanism by which MSTN $^{-/-}$

muscle displays less fibrosis than WT muscle after injury, the expression levels of TGF- $\beta$ 1 in injured WT mice *versus* that expressed in injured MSTN $^{-/-}$  mice should be compared more closely.

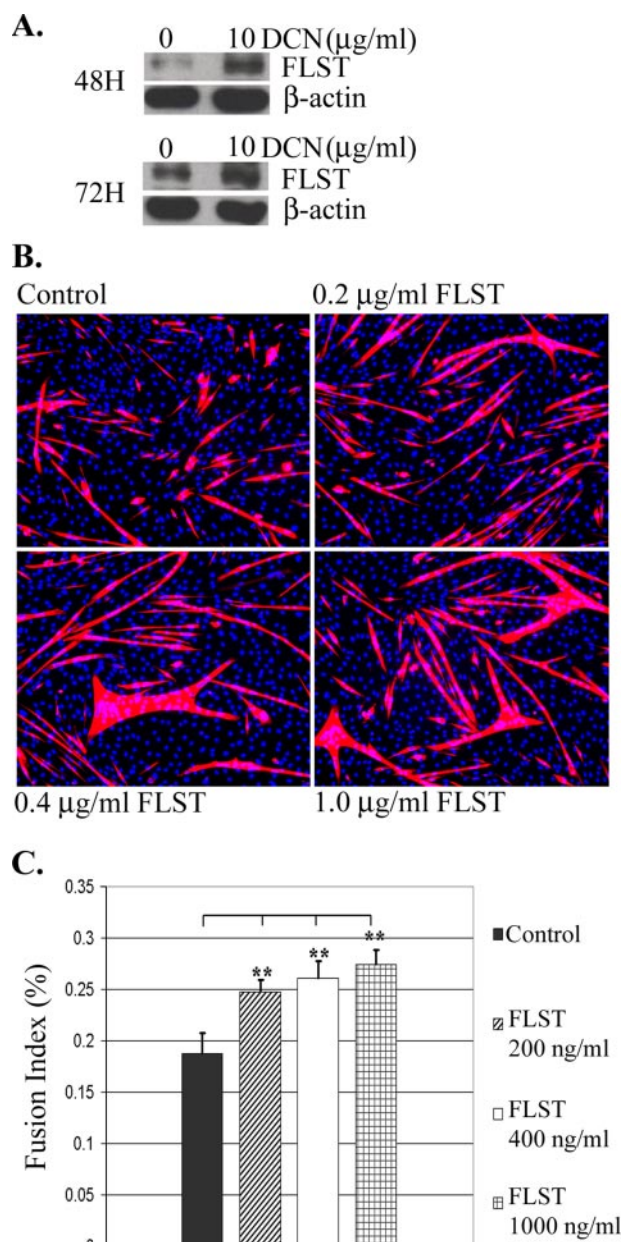
As members of the TGF- $\beta$  superfamily, TGF- $\beta$ 1 and MSTN share many similarities in structure, signaling pathway, and function (52, 53). It has also been shown that TGF- $\beta$ 1 plays a critical role in skeletal muscle fibrosis after injury (20, 26–32). Because both TGF- $\beta$ 1 and MSTN promote fibrosis, it is very important to understand the potential relationships between these two molecules. Recent reports demonstrated that exogenous TGF- $\beta$ 1 strongly stimulated the expression of MSTN in C2C12 myoblasts (44). In fact, our *in vitro* data show that TGF- $\beta$ 1 increases MSTN expression in C2C12 myoblasts (and *vice versa*), and TGF- $\beta$ 1 and MSTN are found to co-localize in the same myofibers shortly after MSTN injection or after injury.

We found that MSTN is able to induce its autocrine expression in both fibroblasts and myoblasts. In the presence of soluble T $\beta$ RII, MSTN autocrine expression in fibroblasts is decreased. We have known that MSTN inhibits C2C12 myoblast differentiation. When T $\beta$ RIIs are blocked by soluble T $\beta$ RII, the ability of MSTN to inhibit C2C12 myoblast differentiation is reduced. Apart from that, Q-RT-PCR results show that

MSTN also stimulates TGF- $\beta$ 1 mRNA expression in PP1 fibroblasts. Our previous study has shown that TGF- $\beta$ 1 is able to induce autocrine expression of TGF- $\beta$ 1 in C2C12 myoblasts (20), nevertheless, our present data revealed that TGF- $\beta$ 1 failed to induce its autocrine expression in MSTN $^{-/-}$  primary muscle cells. Although TGF- $\beta$ 1 and MSTN may target different cell membrane receptors (52), our results suggest that they may also bind to the same receptor, indicating that their signaling may be somehow related. It is likely, then, that the inducement of skeletal muscle fibrosis by TGF- $\beta$ 1 is partially mediated by its interaction with MSTN. However, the mechanism by which TGF- $\beta$ 1 interacts with MSTN to cause fibrosis warrants further investigation.

Satellite cells serve as a reservoir of myogenic progenitor cells for the repair and maintenance of skeletal muscle. MSTN negatively regulates self-renewal and differentiation of satellite





**FIGURE 7. The elevated FLST expression by DCN and the capacity of FLST to enhance myogenic differentiation of C2C12 myoblasts.** A, DCN increased the expression of FLST in C2C12 myoblasts 48 and 72 h after treatment. B, immunofluorescence analysis of myotubes. C2C12 myoblasts were maintained in DM for 5 days in the presence of different concentrations of FLST. Myotubes were double-labeled with an antibody recognizing skeletal myosin heavy chain and with the fluorescent nuclear dye Hoechst 33258 (magnification,  $\times 100$ ). C, fusion indexes were calculated to evaluate the degree of C2C12 myoblast differentiation upon FLST stimulation.

cells (54) and decreases the expression of members of the basic helix-loop-helix muscle regulatory factors (MRF) (MyoD, Myf5, myf4, and myogenin) (43, 55).  $MSTN^{-/-}$  mice show an increased number of satellite cells activated and differentiated toward a myogenic lineage (54). In this study, our data demonstrate that  $MSTN^{-/-}$  mice contain regenerating myofibers with significantly larger diameters than WT mice at 2 and 4 weeks after GM laceration. The increased number of satellite cells in  $MSTN^{-/-}$  mice could, in part, explain the enhanced regeneration revealed by the larger diameter of regenerated

myofibers in  $MSTN^{-/-}$  mice compared with WT mice. Indeed, it has been reported that blocking MSTN signals by isolating myoblasts from transgenic mice carrying the mutated MSTN receptor results in improved success of myoblast transplantation in *mdx* mice compared with normal myoblasts (56). Our results show that  $MSTN^{-/-}$  LTP more readily undergo myogenic differentiation *in vitro* and regenerate skeletal muscle *in vivo* in a more effective manner than wild-type cells.

Furthermore, high levels of MSTN protein have been reported within necrotic fibers in the skeletal muscles of rats damaged by notexin (57), and Western blot analysis revealed the up-regulation of MSTN protein at early time points following notexin-induced injury in rat skeletal muscle (58). Interestingly, it has been shown that MSTN interferes with the chemotaxis of macrophages *in vitro* (51); recombinant MSTN protein significantly reduces the migration of macrophages and myoblasts toward chemoattractants *in vitro*, which likely promotes skeletal muscle regeneration (51). These results suggest that MSTN could impede recruitment of macrophages and myoblasts into the injured site *in vivo*. Macrophages infiltrate damaged tissue to remove debris that could hinder muscle regeneration. Macrophages also secrete a variety of growth factors and cytokines that have chemotactic and/or mitogenic effects on muscle precursor cells, thereby accelerating muscle regeneration (59–63). Compared with WT mice,  $MSTN^{-/-}$  mice have shown elevated recruitment of macrophages and myoblasts and an accelerated inflammatory response after muscle injury (51). These results suggest that the earlier initiation of skeletal muscle regeneration in the injured skeletal muscle of  $MSTN^{-/-}$  mice compared with the injured muscle of WT mice may be due, in part, to accelerated removal of muscle debris. When we monitored the expression of MSTN at the injured site for up to 30 days after injury, we observed an intense expression of MSTN in the cytoplasm of degenerative myofibers 1 and 3 days after laceration. On day 5 after injury, MSTN signal was detected in the cytoplasm of regenerating myofibers. Our results show that the MSTN signal decreases with maturation of regenerating myofibers. Interestingly, there is strong MSTN immunostaining in regenerating small myotubes lacking basal lamina 7 and 14 days post-injury. During skeletal muscle healing (following active muscle regeneration at early time points after injury) fibrosis initiates  $\sim 1$  week post-injury, and peaks at 4 weeks (10, 15, 64). Li *et al.* (20) reported that some regenerating myofibers probably differentiate into myofibroblasts to contribute the formation of fibrosis. This correlation between fibrosis development and increased MSTN and TGF- $\beta$ 1 expression (20) in the early phase of healing may suggest the differentiation of regenerating myotubes/myofibers into myofibroblasts and a potential interaction between TGF- $\beta$ 1, MSTN, and DCN, as previously hypothesized (65).

MSTN-positive signals were also seen within the nuclei of the newly formed fibers at 5, 7, and 10 days post-injury. The nuclear localization of MSTN is supported by previous studies indicating that MSTN was detected in the nuclei of myoblasts and myotubes (66). Consequently, MSTN protein might modulate the muscle fiber regeneration process through the early events of phagocytosis and inflammation (57) and later control myofiber maturation. In this way, MSTN seems to act as a reg-

ulatory molecule that is produced by the tissue to specifically suppress and control the size of muscle growth and development (67).

DCN, a small chondroitin-dermatan sulfate leucine-rich proteoglycan, exists ubiquitously in the ECM. Due to its binding to and inhibition of TGF- $\beta$ 1, DCN has been used as a potent anti-fibrosis agent in various organs and tissues (26, 27, 37–40), including skeletal muscle (26, 27). However, the ability of DCN to regulate MSTN activity is still unknown. DCN, which is composed of a core protein and a single glycosaminoglycan chain (68, 69), has the ability to bind to TGF- $\beta$ 1 due to the fact that the core protein of DCN contains two binding sites for TGF- $\beta$ 1 (70). Similarly, Miura *et al.* (65) have shown that DCN, or the core protein of DCN, directly binds to active MSTN molecules to block MSTN-mediated inhibition of C2C12 myoblast proliferation. The actual location of the MSTN binding site in the DCN core protein and evidence that shows whether TGF- $\beta$ 1 and MSTN competitively bind to DCN are topics for further investigation. Of further interest is the possibility that DCN may regulate MSTN by influencing another intermediate molecule like FLST, an antagonist of MSTN (46). Our results not only show that DCN reduces the effects of MSTN on fibroblasts and myoblasts, but also indicates that it stimulates the expression of FLST in C2C12 myoblasts. Exogenous FLST then stimulates C2C12 myoblast differentiation, which is probably due to FLST's neutralization of endogenous MSTN. These results indicate that the effect of DCN on MSTN may be related to the up-regulation of FLST, which would consequently suppress MSTN activity. Nevertheless, more experiments that would, for example, examine the effect of DCN on FLST knock-out cells, need to be done to establish the role of FLST in DCN-inhibited MSTN activity. Furthermore, we have shown that TGF- $\beta$ 1 probably plays a role in the MSTN signaling pathway, because TGF- $\beta$ 1-soluble receptor antagonizes, at least in part, the effect of myostatin on muscle cells. Overall, DCN probably regulates MSTN activity via three ways: (i) directly binding MSTN, (ii) indirectly down-regulate MSTN by binding to TGF- $\beta$ 1, and (iii) indirectly down-regulating MSTN by stimulating FLST expression.

In summary, our results suggest the following: (i) MSTN stimulates the formation of fibrosis in skeletal muscle after injury, (ii) TGF- $\beta$ 1 and MSTN up-regulate the expression level of each other, and (iii) DCN is capable of inhibiting MSTN activity as it does for TGF- $\beta$ 1. These results, combined with the fact that TGF- $\beta$ 1 plays a key role in skeletal muscle fibrosis and that DCN reduces fibrosis in injured skeletal muscle, suggest that TGF- $\beta$ 1 and MSTN probably act together; they synergistically amplify the fibrotic process in injured or diseased skeletal muscles resulting in greater fibrosis than either could induce individually.

Our findings may help to further increase the understanding of the mechanism by which MSTN<sup>-/-</sup> mice show decreased fibrosis and enhanced regeneration after injury and suggest that the inhibition of MSTN might be a new therapeutic approach for improving skeletal muscle healing through enhancement of regeneration and reduction of fibrosis.

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## REFERENCES

1. Beiner, J. M., and Jokl, P. (2001) *J. Am. Acad. Orthop. Surg.* **9**, 227–237
2. Garrett, W. E., Jr. (1996) *Am. J. Sports Med.* **24**, Suppl. 6, S2–S8
3. Jarvinen, M. J., and Lehto, M. U. (1993) *Sports Med.* **15**, 78–89
4. McLennan, I. S. (1985) *Exp. Neurol.* **89**, 616–621
5. McLennan, I. S. (1987) *Muscle Nerve* **10**, 801–809
6. Mishra, D. K., Friden, J., Schmitz, M. C., and Lieber, R. L. (1995) *J. Bone Joint Surg. Am.* **77**, 1510–1519
7. Obremsky, W. T., Seaber, A. V., Ribbeck, B. M., and Garrett, W. E., Jr. (1994) *Am. J. Sports Med.* **22**, 558–561
8. Shen, W., Li, Y., Tang, Y., Cummins, J., and Huard, J. (2005) *Am. J. Pathol.* **167**, 1105–1117
9. Schultz, E., Jaryszak, D. L., and Valliere, C. R. (1985) *Muscle Nerve* **8**, 217–222
10. Li, Y., Cummins, H. J., and Huard, J. (2001) *Curr. Opin. Orthop.* **12**, 409–415
11. Huard, J., Li, Y., and Fu, F. H. (2002) *J. Bone Joint Surg. Am.* **84-A**, 822–832
12. Jarvinen, M. (1975) *Acta Pathol. Microbiol. Scand. A* **83**, 269–282
13. Jarvinen, M. (1976) *Acta Chir. Scand.* **142**, 47–56
14. Jarvinen, M., and Sorvari, T. (1975) *Acta Pathol. Microbiol. Scand. A* **83**, 259–265
15. Lehto, M., Jarvinen, M., and Nelimarkka, O. (1986) *Arch. Orthop. Trauma Surg.* **104**, 366–370
16. Border, W. A., and Noble, N. A. (1994) *N. Engl. J. Med.* **331**, 1286–1292
17. Lijnen, P. J., Petrov, V. V., and Fagard, R. H. (2000) *Mol. Genet. Metab.* **71**, 418–435
18. Waltenberger, J., Lundin, L., Oberg, K., Wilander, E., Miyazono, K., Heldin, C. H., and Funa, K. (1993) *Am. J. Pathol.* **142**, 71–78
19. Yamamoto, T., Noble, N. A., Miller, D. E., and Border, W. A. (1994) *Kidney Int.* **45**, 916–927
20. Li, Y., Foster, W., Deasy, B. M., Chan, Y., Prisk, V., Tang, Y., Cummins, J., and Huard, J. (2004) *Am. J. Pathol.* **164**, 1007–1019
21. Bernasconi, P., Torchiana, E., Confalonieri, P., Brugnoli, R., Barresi, R., Mora, M., Cornelio, F., Morandi, L., and Mantegazza, R. (1995) *J. Clin. Invest.* **96**, 1137–1144
22. Gosselin, L. E., Williams, J. E., Deering, M., Brazeau, D., Koury, S., and Martinez, D. A. (2004) *Muscle Nerve* **30**, 645–653
23. Desmouliere, A., Geinoz, A., Gabbiani, F., and Gabbiani, G. (1993) *J. Cell Biol.* **122**, 103–111
24. Tomasek, J. J., Gabbiani, G., Hinz, B., Chaponnier, C., and Brown, R. A. (2002) *Nat. Rev. Mol. Cell Biol.* **3**, 349–363
25. Li, Y., and Huard, J. (2002) *Am. J. Pathol.* **161**, 895–907
26. Sato, K., Li, Y., Foster, W., Fukushima, K., Badlani, N., Adachi, N., Usas, A., Fu, F. H., and Huard, J. (2003) *Muscle Nerve* **28**, 365–372
27. Fukushima, K., Badlani, N., Usas, A., Riano, F., Fu, F., and Huard, J. (2001) *Am. J. Sports Med.* **29**, 394–402
28. Foster, W., Li, Y., Usas, A., Somogyi, G., and Huard, J. (2003) *J. Orthop. Res.* **21**, 798–804
29. Chan, Y. S., Li, Y., Foster, W., Horaguchi, T., Somogyi, G., Fu, F. H., and Huard, J. (2003) *J. Appl. Physiol.* **95**, 771–780
30. Chan, Y. S., Li, Y., Foster, W., Fu, F. H., and Huard, J. (2005) *Am. J. Sports Med.* **33**, 43–51
31. Li, Y., Negishi, S., Sakamoto, M., Usas, A., and Huard, J. (2005) *Ann. N. Y. Acad. Sci.* **1041**, 395–397
32. Negishi, S., Li, Y., Usas, A., Fu, F. H., and Huard, J. (2005) *Am. J. Sports Med.* **33**, 1816–1824
33. Wagner, K. R., McPherron, A. C., Winik, N., and Lee, S. J. (2002) *Ann. Neurol.* **52**, 832–836
34. McPherron, A. C., Lawler, A. M., and Lee, S. J. (1997) *Nature* **387**, 83–90
35. McPherron, A. C., and Lee, S. J. (1997) *Proc. Natl. Acad. Sci. U. S. A.* **94**,

- 12457–12461
36. Williams, M. S. (2004) *N. Engl. J. Med.* **351**, 1030–1031; author reply 1030–1031
  37. Giri, S. N., Hyde, D. M., Braun, R. K., Gaarde, W., Harper, J. R., and Pier-schbacher, M. D. (1997) *Biochem. Pharmacol.* **54**, 1205–1216
  38. Grisanti, S., Szurman, P., Warga, M., Kaczmarek, R., Ziemssen, F., Tatar, O., and Bartz-Schmidt, K. U. (2005) *Invest. Ophthalmol. Vis. Sci.* **46**, 191–196
  39. Huijun, W., Long, C., Zhigang, Z., Feng, J., and Muiy, G. (2005) *Exp. Mol. Pathol.* **78**, 17–24
  40. Shimizu, I. (2001) *Curr. Drug. Targets Infect. Disord.* **1**, 227–240
  41. Qu-Petersen, Z., Deasy, B., Jankowski, R., Ikezawa, M., Cummins, J., Pruchnic, R., Mytinger, J., Cao, B., Gates, C., Wernig, A., and Huard, J. (2002) *J. Cell Biol.* **157**, 851–864
  42. Thomas, M., Langley, B., Berry, C., Sharma, M., Kirk, S., Bass, J., and Kambadur, R. (2000) *J. Biol. Chem.* **275**, 40235–40243
  43. Langley, B., Thomas, M., Bishop, A., Sharma, M., Gilmour, S., and Kam-badur, R. (2002) *J. Biol. Chem.* **277**, 49831–49840
  44. Budasz-Rwiderska, M., Jank, M., and Motyl, T. (2005) *J. Physiol. Pharma-col.* **56**, Suppl. 3, 195–214
  45. Yamazaki, K., Fukata, H., Adachi, T., Tainaka, H., Kohda, M., Yamazaki, M., Kojima, K., Chiba, K., Mori, C., and Komiyama, M. (2005) *Mol. Reprod. Dev.* **72**, 291–298
  46. Amthor, H., Nicholas, G., McKinnell, L., Kemp, C. F., Sharma, M., Kam-badur, R., and Patel, K. (2004) *Dev. Biol.* **270**, 19–30
  47. Yamanouchi, K., Soeta, C., Naito, K., and Tojo, H. (2000) *Biochem. Bio-phys. Res. Commun.* **270**, 510–516
  48. Pierce, G. F., Mustoe, T. A., Lingelbach, J., Masakowski, V. R., Griffin, G. L., Senior, R. M., and Deuel, T. F. (1989) *J. Cell Biol.* **109**, 429–440
  49. Phan, S. H. (2002) *Chest* **122**, Suppl. 6, 286S–289S
  50. Thannickal, V. J., Toews, G. B., White, E. S., Lynch, J. P., 3rd, and Martinez, F. J. (2004) *Annu. Rev. Med.* **55**, 395–417
  51. McCroskery, S., Thomas, M., Platt, L., Hennebry, A., Nishimura, T., McLeay, L., Sharma, M., and Kambadur, R. (2005) *J. Cell Sci.* **118**, 3531–3541
  52. Rebbapragada, A., Benchabane, H., Wrana, J. L., Celeste, A. J., and Atti-sano, L. (2003) *Mol. Cell. Biol.* **23**, 7230–7242
  53. Zhu, X., Topouzis, S., Liang, L. F., and Stotish, R. L. (2004) *Cytokine* **26**, 262–272
  54. McCroskery, S., Thomas, M., Maxwell, L., Sharma, M., and Kambadur, R. (2003) *J. Cell Biol.* **162**, 1135–1147
  55. Joulia, D., Bernardi, H., Garandel, V., Rabenoelina, F., Vernus, B., and Cabello, G. (2003) *Exp. Cell Res.* **286**, 263–275
  56. Benabdallah, B. F., Bouchentouf, M., and Tremblay, J. P. (2005) *Trans-plantation* **79**, 1696–1702
  57. Kirk, S., Oldham, J., Kambadur, R., Sharma, M., Dobbie, P., and Bass, J. (2000) *J. Cell. Physiol.* **184**, 356–363
  58. Mendler, L., Zador, E., Ver Heyen, M., Dux, L., and Wuytack, F. (2000) *J. Muscle Res. Cell Motil.* **21**, 551–563
  59. Cantini, M., Massimino, M. L., Bruson, A., Catani, C., Dalla Libera, L., and Carraro, U. (1994) *Biochem. Biophys. Res. Commun.* **202**, 1688–1696
  60. Chazaud, B., Sonnet, C., Lafuste, P., Bassez, G., Rimaniol, A. C., Poron, F., Authier, F. J., Dreyfus, P. A., and Gherardi, R. K. (2003) *J. Cell Biol.* **163**, 1133–1143
  61. Lescaudron, L., Peltekian, E., Fontaine-Perus, J., Paulin, D., Zampieri, M., Garcia, L., and Parrish, E. (1999) *Neuromuscul. Disord.* **9**, 72–80
  62. Merly, F., Lescaudron, L., Rouaud, T., Crossin, F., and Gardahaut, M. F. (1999) *Muscle Nerve* **22**, 724–732
  63. Robertson, T. A., Maley, M. A., Grounds, M. D., and Papadimitriou, J. M. (1993) *Exp. Cell Res.* **207**, 321–331
  64. Menetrey, J., Kasemkijwattana, C., Fu, F. H., Moreland, M. S., and Huard, J. (1999) *Am. J. Sports Med.* **27**, 222–229
  65. Miura, T., Kishioka, Y., Wakamatsu, J., Hattori, A., Hennebry, A., Berry, C. J., Sharma, M., Kambadur, R., and Nishimura, T. (2006) *Biochem. Bio-phys. Res. Commun.* **340**, 675–680
  66. Artaza, N. J., Bhasin, S., Mallidis, C., Taylor, W., Ma, K., and Gonzalez-Cadavid, F. N. (2002) *J. Cell. Physiol.* **190**, 170–179
  67. Kocamis, H., and Killefer, J. (2002) *Domest. Anim. Endocrinol.* **23**, 447–454
  68. Yamaguchi, Y., and Ruoslahti, E. (1988) *Nature* **336**, 244–246
  69. Krusius, T., and Ruoslahti, E. (1986) *Proc. Natl. Acad. Sci. U. S. A.* **83**, 7683–7687
  70. Schonherr, E., Broszat, M., Brandan, E., Bruckner, P., and Kresse, H. (1998) *Arch. Biochem. Biophys.* **355**, 241–248



## DECORIN INTERACTS WITH MYOSTATIN ACTIVITY – IMPLICATIONS FOR SKELETAL MUSCLE HEALING

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jhuard@pitt.edu**Introduction:**

Skeletal muscle injuries are one of the most common injuries occurring in field of sports medicine. Muscle injuries can heal spontaneously via regeneration, but fibrosis usually impedes this process which results in incomplete functional recovery. We have demonstrated that TGF- $\beta$ 1 plays a major role in the initiation of fibrosis in injured muscle [1]. Decorin, a small chondroitin-dermatan sulphate leucine-rich proteoglycan, has been shown to improve skeletal muscle healing histologically and physiologically through a concomitant increase in muscle regeneration and a decrease in fibrosis [2]. It is widely accepted that the antifibrotic effect of decorin primarily results from its capability of directly binding to and neutralizing TGF- $\beta$ 1 [3]. The identification of a new TGF- $\beta$  family member, myostatin (MSTN) [4], has inspired us to further explore the mechanism by which decorin improves skeletal muscle healing. Our unpublished data showed that 1) MSTN stimulates proliferation and myofibroblastic differentiation of fibroblasts in vitro; 2) that the injured skeletal muscle of MSTN knockout (MSTN<sup>-/-</sup>) mice contains significantly less fibrous scar tissue than observed in the injured muscle of normal wild-type (WT) mice and 3) regenerating myofibers of MSTN<sup>-/-</sup> mice are significantly larger in diameter than those in the injured muscle of WT mice. Thus MSTN, like TGF- $\beta$ 1, appears to play an important role in fibrosis. We performed this study to investigate whether decorin could inhibit the activity of MSTN as it does with TGF- $\beta$ 1.

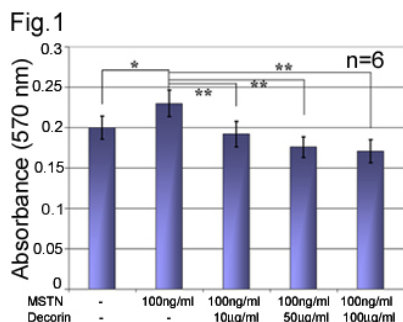
**Methods:**

**Proliferation assay and Western blot analysis:** PP1 fibroblasts were plated onto collagen-coated 96-well plates for cell proliferation analysis. Following overnight attachment, normal medium was replaced with serum free medium plus serum replacement (Sigma, St Louis, MO) in the presence of varying concentrations of decorin and 100ng/ml of recombinant human MSTN. After an additional incubation for 48 h, an MTT cell proliferation assay kit (Roche Diagnostics, Germany) was used to measure cell proliferation ( $n = 6$ ) following instructions from the manufacturer. Western blot was used to examine  $\beta$ -actin and MSTN expression. To test whether decorin neutralized the inhibitory effect of MSTN on myogenic cell differentiation, C2C12 myoblasts were seeded in 12-well plates at a density of 10,000 cells/well. After overnight incubation, medium was replaced with fresh differentiation medium (DM) containing DMEM, 2% HS, and 1% P/S, with or without addition of 1 $\mu$ g/ml MSTN. This was concomitant with the addition of 0-100  $\mu$ g/ml decorin ( $n = 3$ ). Cells were cultured for another 5 days. DM, MSTN, and decorin were changed every other day.

**Injury model:** All experiments in this study were in accordance with research protocols approved by the ARCC of Children's Hospital of Pittsburgh. MSTN-deficient mice (MSTN<sup>-/-</sup>) and C57BL/6J wild-type mice (control) were used to establish an injury model of skeletal muscle laceration [2]. GMs of both MSTN<sup>-/-</sup> and wild-type mice were harvested 2 weeks after laceration. Decorin immunostaining was performed to evaluate decorin expression in injured skeletal muscle. Student's *t*-test or one way ANOVA were used to determine significance ( $P < 0.05$ ).

**Results:**

**Blockade of MSTN effect on fibroblasts by Decorin:** After PP1 fibroblasts were incubated with MSTN and varying concentrations of decorin for 48 h, MTT assay revealed that 0.1 $\mu$ g/ml MSTN significantly stimulated PP1 fibroblast proliferation whereas the addition of decorin significantly



repressed the MSTN stimulatory effect on PP1 proliferation (Fig 1).

**Decorin blocks MSTN autocrine**

**expression in fibroblasts:** After 48 h incubation, PP1 fibroblasts did not express detectable MSTN protein, and

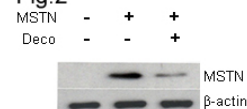
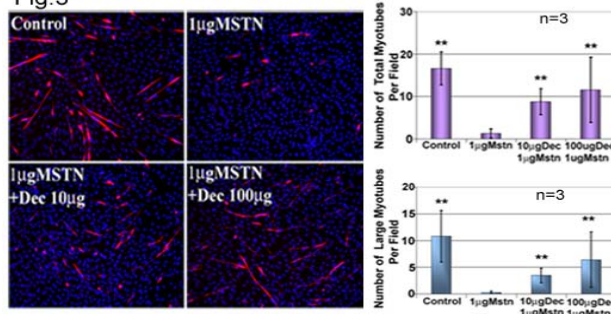
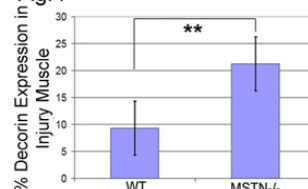
PP1 fibroblasts treated with MSTN showed a high level of MSTN expression. However, MSTN expression in PP1 fibroblasts treated with both MSTN and decorin was reduced to only a detectable level (Fig 2).

**Blockade of MSTN effect on C2C12 myoblast differentiation by Decorin**

Following a 5-day incubation, controls showed widespread skeletal muscle heavy chain (MHC) positive myotubes whereas cells treated with MSTN alone contained few myotubes (Fig 3). The addition of decorin reversed the inhibition of MSTN on myogenic differentiation (Fig 3). Quantification showed that decorin treatment significantly promoted C2C12 myoblast fusion and increased the number and size of the myotubes in the presence of MSTN (Fig 3) in a dose dependent manner

**Elevated decorin expression in injured MSTN<sup>-/-</sup> mice**

Immunohistochemical staining revealed that there was a significantly higher level of decorin expression in the regenerating skeletal muscle of MSTN<sup>-/-</sup> mice than that of WT mice 2 weeks after injury (Fig 4).

**Fig.2****Fig.3****Fig.4****Discussion:**

In this study, we showed that decorin blocked the effects of MSTN on both fibroblasts and myoblasts in vitro. Decorin reduced the stimulating effects of MSTN on fibroblasts and the MSTN autocrine expression of fibroblasts. Moreover, decorin rescued the inhibitory effect of MSTN on myoblast differentiation. The ability of decorin to bind to TGF- $\beta$ 1 is due to the fact that core protein of decorin contains two binding sites for TGF- $\beta$ 1. Similarly, it has been recently shown that decorin, or the core protein of decorin, can directly bond to active MSTN molecules to block MSTN-mediated inhibition of C2C12 myoblast proliferation [5]. The location of the MSTN binding site in the decorin core protein and whether TGF- $\beta$ 1 and MSTN competitively bind to decorin are topics for further investigation. These findings provide us a better understanding of how decorin can improve skeletal muscle healing after injury.

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**References:** 1. Li Y et al. Am J Pathol 2004;164:1007-19. 2. Fukushima et al. Am J Sports Med 2001; 29(4): 394-402. 3. Yamaguchi et al. Nature 1988; 336(6196): 244-6. 4. McPherron AC et al. Nature 1997;387:83-90. 5. Miura et al. Biochem Biophys Res Commun 2006; 340(2): 675-80.

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## FOLLISTATIN IMPROVES SKELETAL MUSCLE HEALING AFTER INJURY

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## INTRODUCTION

Skeletal muscle injuries account for 10 to 30% of all sports related injuries. Muscle injuries can heal via spontaneous regeneration; however, as a result of severe injury, incomplete functional recovery can increase the time an athlete is off the field. Decorin has been shown to effectively improve skeletal muscle healing by reducing fibrosis and accelerating skeletal muscle regeneration [1]. Aside from decorin, Follistatin (FLST) has been drawing more attention do to the fact that increasing knowledge about this molecule reveals it as a promising new target for therapeutic improvement of skeletal muscle healing. FLST was initially described as an inhibitor of follicle-stimulating hormone decades ago. More and more evidence revealed that FLST is capable of binding and neutralizing many members of the TGF- $\beta$  superfamily such as myostatin (MSTN) and activin [2, 3]. Recently, it was found that FLST overexpression mice (FLST OE) showed dramatic increase in skeletal muscle mass compared to wild-type control mice [4]. Activin is implicated in the formation of fibrosis in many tissues and organs such as skin, liver, and kidney [2, 3]. Furthermore, our unpublished data demonstrated that MSTN is a fibrosis stimulator in the skeletal muscle and blocking MSTN significantly reduces the formation of fibrosis in injured skeletal muscle of mice. Taken together, we hypothesize that FLST may improve the healing of injured skeletal muscle. In this study, transgenic FLST OE mice were used to investigate the influence of FLST on skeletal muscle healing.

## METHODS

**Myoblast differentiation assay:** C2C12 myoblasts were plated onto collagen-coated 12-well plates with normal medium overnight. The following day, the medium was replaced with low serum medium (2% horse serum) plus different concentrations of FLST (Sigma, St. Louis, MO). The cells were cultured for 6 additional days. Medium and recombinant FLST protein were changed every other day. Myotubes were monitored by myosin heavy chain (MHC) immunostaining, and the fusion capacity of C2C12 myoblasts was evaluated by determining the number of myonuclei per myotube ( $n = 3$ ).

**Western blot:** C2C12 myoblasts were plated onto collagen-coated 6-well plates. Following overnight attachment, normal medium was replaced with low serum medium in the presence of decorin (Sigma, St. Louis, MO). Protein samples were collected at 48 and 72h and separated by 10% sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE). Goat anti-follistatin antibody (Santa Cruz Biotechnology, INC. Santa Cruz, CA) was used to detect FLST expression in C2C12 myoblasts

**Animal model:** All experiments in this study were approved by the Children's Hospital of Pittsburgh IACUC. C57BL/6J wide-type (WT) and FLST OE mice (7 to 8 weeks of age) were used for all experiments ( $n = 6$ ). Both gastrocnemius muscles (GMs) of each mouse underwent bilateral laceration [1]. The GMs were harvested 4 weeks after laceration, and Masson's Trichrome staining (nuclei [black], muscle [red], collagen [blue]) was performed to identify fibrous scar tissue in the injured muscles. Northern Eclipse software (Empix Imaging, Inc.) was used to measure areas of fibrous scar tissue and regenerated muscle within the injury site.

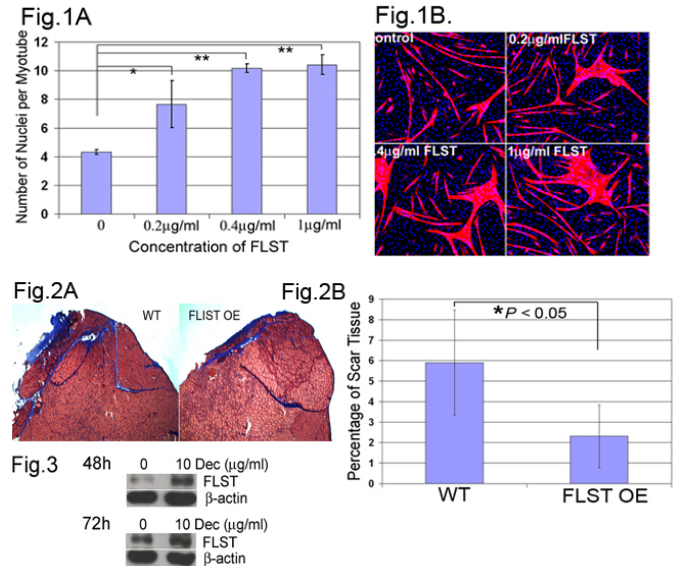
**Statistics:** One-way analysis of variance (ANOVA) followed by post hoc Tukey's multiple comparison test or Student's  $t$  test was used to determine significance ( $P < 0.05$ ) throughout this study. (\*) represents that  $P < 0.05$ , and (\*\*) represents that  $P < 0.01$ ;

## RESULTS

**FLST induces large myotube formation in vitro:** Our results reveal the ability of FLST to stimulate myogenic differentiation as shown in Fig 1. Myotubes treated with FLST were larger and contained more nuclei than the control (Fig. 1A). FLST treatment leads to a significant increase in the number of nuclei per myotubes in a dose dependent manner (Fig. 1B) compared to control, suggesting that FLST promotes myogenic fusion and accelerates the maturation of myotubes.

**Reduced fibrosis in FLST OE mice after GM laceration:** The results of Masson's Trichrome histochemistry revealed significantly less fibrous scar tissue in the FLST OE GMs than in the WT GMs (Fig. 2A, B).

**Decorin stimulates FLST expression in C2C12 myoblasts:** We found that decorin up-regulated FLST expression in C2C12 myoblasts after 48h and 72h of culture (Fig.3).



## DISCUSSION

We have demonstrated that TGF- $\beta$ 1 plays a significant role in both the initiation of fibrosis and the induction of myofibroblastic differentiation by myogenic cells in injured skeletal muscle [6]. Although, FLST improves skeletal muscle healing, it does not seem to block fibrosis in injured skeletal muscle through inhibition of TGF- $\beta$ 1. Our result showed that FLST failed to block the inhibition that TGF- $\beta$ 1 has on myogenic differentiation (data not shown). Most likely, FLST inhibits the formation of fibrosis by antagonizing the activities of activin and MSTN [2, 3]. FLST overexpression improves skeletal muscle healing by reducing fibrosis. Although FLST significantly increases myoblast differentiation in vitro, FLST OE mice did not show increased diameter of regenerating myofibers compared to WT mice at 4 weeks after GM laceration. This suggests that FLST is involved with an alternative mechanism for skeletal muscle healing. Moreover, we also showed that decorin treatment elevated FLST expression in C2C12 myoblasts. It seems likely that, apart from neutralizing TGF- $\beta$ 1, decorin also reduces fibrosis in injured skeletal muscle by up-regulating the intermediate molecule, FLST. The skeletal muscle healing process is a complex process, in which many molecules interact with each other, and our findings provide insight into one aspect of this network.

## ACKNOWLEDGMENTS

This work was supported by funding from the Henry J. Mankin Endowed Chair for Orthopaedic Research at the University of Pittsburgh, the William F. and Jean W. Donaldson Chair at Children's Hospital of Pittsburgh, the Hirtzel Foundation, and the National Institutes of Health (R01 AR47973). The FLST OE mice were a gift from Dr. Se-Jin Lee (Johns Hopkins University).

## REFERENCES

1. Fukushima et al. Am J Sports Med 2001;29(4):394-402.
2. Phillips et al. Front Neuroendocrinol 1998 ;225 :127-32.
3. Amthor, H., et al., Dev Biol 2004. 270(1): 19-30.
4. Lee SJ et al. Proc Natl Acad Sci USA 2001;98:9306-11.
5. Sulyok et al. Mol Cell Endocrinol 2004;118:3531-41.
6. Li Y et al. Am J Pathol 2004;164:1007-19.

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## Suramin can enhance the skeletal muscle healing by blocking myostatin

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### INTRODUCTION:

Muscle injuries are very common musculoskeletal problems encountered in sports medicine. Although this type of injury is capable of healing, complete functional recovery is hindered by the development of scar tissue formation triggered by TGF- $\beta$ 1 [1]. We already reported suramin can effectively prevent the formation of fibrotic scar and block the proliferative effect of TGF- $\beta$ 1 on fibroblasts and can stimulate the differentiation on myogenic cells *in vitro* (unpublished data). Thus suramin can enhance muscle regeneration in the lacerated and strain-injured muscle [2, 3]. Furthermore we also reported blockade of myostatin (MSTN), a member of TGF- $\beta$  super family, by decorin, other anti-fibrotic agent, showed enhancement of the fusion on myoblasts and inhibitory effect of fibroblast proliferation *in vitro* [4]. This finding brought us more interest to investigate another pathway of suramin to regulate fibroblasts and myoblasts by blocking the effect of MSTN. We performed this study to examine whether suramin would block MSTN's proliferative effect on fibroblasts and inhibitory effect of myoblasts differentiation *in vitro* and reduce the expression of MSTN in injured muscle to improve muscle healing *in vivo*, using an animal model of muscle contusion.

### MATERIALS AND METHODS:

**3T3 cell proliferation assay:** 3T3 fibroblasts were cultured in 96 well plates (n=5) with DMEM containing 2% serum replacement (Sigma, St Louis, MO) and different concentration of MSTN (0 and 1  $\mu$ g/ml) and suramin (0 and 50  $\mu$ g/ml). Three days after incubation CellTiter Cell Proliferation Assay kit (Promega, Madison, WI) was used to measure cell proliferation.

**C2C12 cell differentiation assay:** C2C12 myoblasts were cultured in 24 well plates (n=4) with differentiation medium (DMEM containing 2% horse serum and 1% penicillin/streptomycin) containing different concentration of MSTN (0 and 1  $\mu$ g/ml) and suramin (0, 1, and 25  $\mu$ g/ml). Three days after incubation immunocytochemistry of myosin heavy chain was done and the fusion index was assessed by counting the number of nuclei in differentiated myotubes as a percentage of the total number of nuclei.

**Animal model:** The muscle contusion model was developed in tibialis anterior muscle of normal wild-type mice. Different concentrations of suramin (0 and 2.5 mg in 20  $\mu$ l of Phosphate-buffered solution [PBS]) were injected intramuscularly two weeks after injury (five mice in each group). Cryostat sections of muscles were obtained and histologically stained (hematoxylin and eosin stain (H&E) and Masson's Trichrome stain) to evaluate the regeneration by counting the number of centronucleated regenerating myofibers and measuring fibrosis four weeks after injury. Specific peak force and specific tetanic force were measured as physiological tests to evaluate functional recovery after muscle injury using same protocol as above (five mice in each group). Furthermore immunohistochemistry of MSTN was performed at different time point (0.5, 1, 2, 10 days after suramin (0 and 2.5 mg) injection) to evaluate the expression of MSTN (five mice in each group at each time point). Northern Eclipse software (Empix Image, Inc.) was used to quantify the total fibrotic area and expression of MSTN. Statistical analysis was performed with student's t-test or ANOVA. Statistical significance was defined as  $P < .05$  (\*:  $P < .05$ , \*\*:  $P < .01$ ).

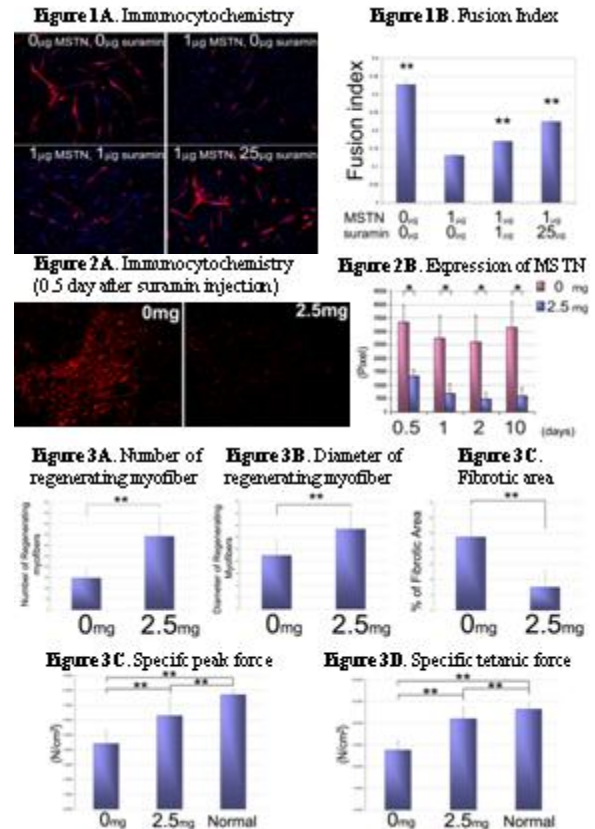
### RESULTS:

**Suramin blocked the proliferative effect of MSTN on fibroblasts and the inhibitory effect of MSDN of myoblast differentiation:** MSTN treatment significantly promoted the proliferation on fibroblasts and the differentiation on myoblasts. However, suramin treatment significantly blocked both of those MSTN's effects and moreover suramin treatment stimulated the fusion on myoblasts in a dose-dependent manner in the presence of MSTN (Fig. 1A, B).

**Suramin inhibits the myostatin expression in injured skeletal muscle:** Suramin (2.5 mg) injection 2 weeks after contusion injury effectively inhibited the expression of MSTN when compared with the control group (0 mg) at different time points (0.5, 1, 2, 10 days after suramin injection) (Fig. 2A, B).

**Suramin enhances muscle regeneration and decreases fibrosis and improves functional recovery after contusion injury:** We observed a

significant increase in the number and in the diameter of regenerating myofibers in the suramin treated group (2.5 mg) when compared with the control group (0mg) (Fig. 3A, B). Moreover suramin treated group showed significantly less fibrotic area than control group (Fig. 3C). Furthermore the suramin treatment showed significant advantage in physiological evaluation (specific peak force and specific tetanic force) compared to control group.



### DISCUSSION:

We have reported that suramin can effectively prevent muscle fibrosis and enhance muscle regeneration by blocking TGF- $\beta$ 1 after laceration and strain injury [2, 3]. Nevertheless, whether suramin would regulate the effect of MSTN, negative regulator of muscle growth, to improve muscle healing was still unknown. This is the first study to show that suramin down-regulates the proliferation on fibroblasts and up-regulates the differentiation on myoblasts by neutralizing MSTN. Moreover suramin injection in injured skeletal muscle effectively inhibited the expression of MSTN and enhanced the muscle regeneration and reduced the fibrosis *in vivo*. These results may reveal the hidden mechanism by which suramin improve the muscle healing after injuries. We have reported important anti-fibrotic molecules such as Decorin to improve injured skeletal muscles. However suramin has been already approved by FDA and this makes suramin more suitable agent for the therapy of muscle injury. Our findings may contribute to the development of biological therapies for muscle injury.

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### REFERENCES:

- Li Y, Foster W *et al.*, *Am J Pathol* 2004;164: 1007-19.
- Chan Y, Li Y *et al.*, *J Appl Physiol* 2003;95:771-80.
- Chan Y, Li Y *et al.*, *Am J Sports Med* 2005; 33:43-51.
- Zhu J, Li Y *et al.*, *J Biol Chem* 2007, in print



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## Improved Muscle Healing After Contusion Injury by the Inhibitory Effect of Suramin on Myostatin, a Negative Regulator of Muscle Growth

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# Improved Muscle Healing After Contusion Injury by the Inhibitory Effect of Suramin on Myostatin, a Negative Regulator of Muscle Growth

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**Background:** Muscle contusions are the most common muscle injuries in sports medicine. Although these injuries are capable of healing, incomplete functional recovery often occurs.

**Hypothesis:** Suramin enhances muscle healing by both stimulating muscle regeneration and preventing fibrosis in contused skeletal muscle.

**Study Design:** Controlled laboratory study.

**Methods:** In vitro: Myoblasts (C2C12 cells) and muscle-derived stem cells (MDSCs) were cultured with suramin, and the potential of suramin to induce their differentiation was evaluated. Furthermore, MDSCs were cocultured with suramin and myostatin (MSTN) to monitor the capability of suramin to neutralize the effect of MSTN. In vivo: Varying concentrations of suramin were injected in the tibialis anterior muscle of mice 2 weeks after muscle contusion injury. Muscle regeneration and scar tissue formation were evaluated by histologic analysis and functional recovery was measured by physiologic testing

**Results:** In vitro: Suramin stimulated the differentiation of myoblasts and MDSCs in a dose-dependent manner. Moreover, suramin neutralized the inhibitory effect of MSTN on MDSC differentiation. In vivo: Suramin treatment significantly promoted muscle regeneration, decreased fibrosis formation, reduced myostatin expression in injured muscle, and increased muscle strength after contusion injury.

**Conclusion:** Intramuscular injection of suramin after a contusion injury improved overall skeletal muscle healing. Suramin enhanced myoblast and MDSC differentiation and neutralized MSTN's negative effect on myogenic differentiation in vitro, which suggests a possible mechanism for the beneficial effects that this pharmacologic agent exhibits in vivo.

**Clinical Relevance:** These findings could contribute to the development of biological treatments to aid in muscle healing after experiencing a muscle injury.

**Keywords:** muscle contusion injury; suramin; myostatin; muscle regeneration; fibrosis

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Muscle injuries are common musculoskeletal problems encountered in sports medicine clinics. Muscle contusion,

produced by the impact of a nonpenetrating object,<sup>8</sup> is one of the most common muscle injuries.<sup>3</sup> Current therapies including RICE (rest, ice, compression, and elevation), immobilization, as well as active and passive range of motion exercise are the norm for treatment; however, complications such as muscle atrophy, contracture formation, and pain leading to functional and structural deficits often occur after severe muscle injury.<sup>8,24,25,38</sup> Optimal treatment strategies have not yet been clearly defined.

We have observed that the healing process of injured skeletal muscle in animal models consists of 3 distinct phases:

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degeneration and inflammation, regeneration, and fibrosis.<sup>13,15,16,26</sup> The first phase, which occurs in the first few days after injury, is characterized by local swelling at the injury site, the formation of a hematoma, necrosis of muscle tissue,<sup>20,23</sup> degeneration, and an inflammatory response, which consists of the infiltration of activated macrophages and T-lymphocytes into the injured tissue. The next phase, regeneration, usually occurs 5 to 10 days after injury and includes phagocytosis of the damaged tissue and regeneration of the injured muscle. This phase is promoted by the release of several growth factors that regulate myoblast proliferation and differentiation, produce connective tissue and scar tissue, and induce capillary ingrowth at the injury site.<sup>1,4,17</sup>

The final phase, the formation of scar tissue (fibrosis), usually begins between the second and third week after injury. The formation of scar appears to be the end product of the muscle repair process and hinders full muscle regeneration. We have previously reported that transforming growth factor- $\beta$ 1 (TGF- $\beta$ 1) is a major factor in triggering the fibrotic cascade within injured skeletal muscle.<sup>30,31</sup> With this in mind, we have focused on the use of antifibrotic agents (such as decorin and  $\gamma$ -interferon) that inhibit TGF- $\beta$ 1 expression, reduce scar tissue formation, and consequently improve muscle healing after injury.<sup>12,13</sup> Administration of decorin after muscle injury showed improvement of muscle healing both histologically and physiologically.<sup>13</sup> The injection of  $\gamma$ -interferon into injured skeletal muscle also showed similar effects.<sup>12</sup> Despite these compelling findings, which were derived from various murine injury models, the fact that decorin is not clinically available limits its translation to human subjects and  $\gamma$ -interferon demonstrates serious side effects in spite of US Food and Drug Administration (FDA) approval. A recently published study has shown that myostatin (MSTN), a member of the TGF- $\beta$  superfamily and a negative regulator of muscle growth, stimulates scar tissue formation after skeletal muscle injury in vivo.<sup>48</sup> It was also shown in this study that decorin could inhibit MSTN's activity in vitro.<sup>48</sup> Because both decorin and suramin have the ability to inhibit TGF- $\beta$ 1 activity,<sup>5,6,13</sup> we hypothesize that suramin may also possess a similar anti-MSTN activity as decorin.

Suramin, an antiparasitic and antineoplastic agent, can inhibit TGF- $\beta$ 1's ability to bind to its receptors and has been shown to enhance muscle regeneration after strain and laceration injuries.<sup>5,6</sup> We pursued the use of suramin due to the fact that it is currently FDA-approved and could thereby be used clinically more readily than decorin. In the current study, we examine whether suramin can promote differentiation of myoblasts and muscle-derived stem cells (MDSCs) and neutralize the effect of MSTN in vitro. We also investigate whether suramin can improve muscle healing after muscle contusion, a common muscle injury, by enhancing regeneration and reducing fibrosis in vivo.

## MATERIALS AND METHODS

### In Vitro Potential of Suramin to Induce Myogenic Differentiation

*Effect of Suramin on C2C12 Myoblasts.* C2C12 cells, a well-known myoblast cell line, were cultured with Dulbecco's

modified Eagle's medium (DMEM) (Invitrogen, Carlsbad, California) containing 10% fetal bovine serum (FBS) (Invitrogen), and 1% penicillin/streptomycin (P/S) (Invitrogen). Cells were plated at a density of 10 000 cells/well into 12-well plates. After a 24-hour incubation period, the medium was completely removed and low serum-containing medium (DMEM, 2% horse serum [HS] [Invitrogen], and 1% P/S) was added with varying concentrations of suramin (0, 0.25, 2.5, 25  $\mu$ g/mL) (Sigma, St Louis, Missouri). Medium was replaced with fresh medium (containing the same concentrations of suramin) every 2 days. All the cells were grown at 37°C in 5% CO<sub>2</sub> for a total of 4 days.

*Effect of Suramin on MDSCs Isolated From Skeletal Muscle.* MDSCs were isolated from 3-week-old male mice (C57BL10J+/+) via the previously described modified preplate technique.<sup>31,35,36</sup> Muscle-derived stem cells were cultured in proliferation medium (PM) containing DMEM, 10% FBS, 10% HS, 1% P/S, and 0.5% chick embryo extract (Sera Laboratories International, West Sussex, United Kingdom). Cells were plated at a density of 10 000 cells/well into 12-well plates. After a 24-hour incubation period, the medium was completely removed and low-serum medium was added with different concentrations of suramin (0, 1, 10, 100  $\mu$ g/mL) for the next 24 hours. Medium was replaced with fresh low-serum medium for 1 more day. All the cells were grown at 37°C in 5% CO<sub>2</sub> for a total of 3 days.

*Ability of Suramin to Neutralize MSTN's Inhibition of MDSC Differentiation.* Muscle-derived stem cells were cultured in PM and plated at a density of 5000 cells/well into 24-well plates. After a 24-hour incubation period, the medium was removed and low serum-containing medium was added with varying concentrations of suramin (0, 1, 10, or 100  $\mu$ g/mL) and MSTN (0 or 100 ng/mL) for the next 24 hours. Medium was replaced with fresh low serum medium containing the same concentrations of MSTN for 1 additional day. All the cells were grown at 37°C in 5% CO<sub>2</sub> for a total of 3 days.

### Immunocytochemistry

To quantify the differentiation of the C2C12 cells and MDSCs, cells were fixed in cold methanol for 2 minutes and washed in Dulbecco's phosphate-buffered saline (PBS) for 10 minutes at room temperature (RT). Samples were washed 3 times in PBS, then incubated in blocking buffer (10% HS) for 30 minutes at RT. Cells were incubated overnight at 4°C with primary antibodies (monoclonal antiskeletal myosin [fast] clone MY-32 [Sigma]) in 2% HS. After washing in PBS, samples were incubated with the secondary antibody (goat antimouse IgG conjugated with Cy3 [Sigma]) in 2% HS for 1 hour at RT. The cell nuclei were stained with a Hoechst 33258 dye for 10 minutes at RT. Fusion index (ratio of nuclei in myotubes to all nuclei) was calculated to evaluate the myogenic differentiation capacity of cells.

### Evaluation of the Histologic and Physiologic Effects of Suramin on Muscle Healing After Contusion Injury In Vivo

*Animal Model.* The policies and procedures followed for the animal experimentation performed in these studies are

in accordance with those detailed by the US Department of Health and Human Services and the National Institutes of Health *Guide for the Care and Use of Laboratory Animals*. Our Institutional Animal Care and Use Committee approved the research protocol used for these experiments (protocol No. 19/05). An animal model of muscle contusion was developed in normal mice (C57BL6J<sup>+/+</sup>, Jackson Laboratory, Bar Harbor, Maine) based on previously described studies.<sup>8,26</sup> Thirty-three mice, aged 8 to 10 weeks with weights of 21.0 to 26.3 g, were used in this experiment.

The mice were anesthetized with 1.0% to 1.5% isoflurane (Abbott Laboratories, North Chicago, Illinois) in 100% O<sub>2</sub> gas. The mouse's hindlimb was positioned by extending the knee and plantar flexing the ankle 90°. A 16.2-g, 1.6-cm stainless steel ball (Small Parts Inc, Miami Lakes, Florida) was dropped from a height of 100 cm onto the impactor that hit the mouse's tibialis anterior (TA) muscle. The muscle contusion made by this method was a high-energy blunt injury that created a large hematoma and was followed by massive muscle regeneration,<sup>8,26</sup> healing processes that are very similar to those seen in humans.<sup>10</sup> The mice were divided into 4 groups (6 mice/group) on the basis of the different concentrations of suramin to be injected (0, 2.5, 5, and 10 mg in 20  $\mu$ L of PBS) after creating the contusion injury. Suramin was injected 2 weeks after injury. All animals were sacrificed to evaluate the healing histologically and physiologically at 4 weeks after injury. Three mice (6 muscles) per group were assessed histologically, 3 mice (6 muscles) per group were assessed physiologically, and 3 mice were used as normal controls in the physiologic tests.

Furthermore, 2 concentrations of suramin (0 and 2.5 mg in 20  $\mu$ L of PBS) were injected 2 weeks after injury (3 mice/group). The mice of both groups were sacrificed 2 days after injection for histologic analysis of MSTN expression.

**Evaluation of Muscle Regeneration After Suramin Therapy.** Tibialis anterior muscles that were used for histologic evaluation were isolated and frozen in 2-methylbutane precooled in liquid nitrogen and subsequently cryosectioned. Hematoxylin and eosin staining was done to monitor the number of regenerating myofibers within the injury sites treated with suramin (0, 2.5, 5, or 10 mg in 20  $\mu$ L of PBS), and the results were compared among the different groups. Centronucleated myofibers were considered to be regenerating myofibers. Centrally nucleated myofibers are a sign of regeneration in injured and diseased muscle. Upon myoblast fusing into myotubes or with myofibers, the nuclei remain in the endomysial tube found in the center of the myofiber until it has reached maturity whereby the nuclei migrate to their final positions at the periphery of the mature fiber in the subsarcolemmal position. The central nucleation is easily identified by hematoxylin and eosin or trichrome staining.<sup>11,37</sup> Analysis of regenerating myofibers was performed using Northern Eclipse software (Empix Imaging Inc, Cheektawaga, New York). The total number of regenerating myofibers within the injury site was quantified by using 10 random fields selected from each sample in accordance with a previously described protocol.<sup>12,13,26,33</sup>

**Evaluation of Fibrosis After Suramin Therapy.** To measure areas of fibrotic tissue in the injury sites, Masson's trichrome

staining (IMEB Inc, Chicago, Illinois) was performed. After Masson trichrome staining, the ratio of the fibrotic area to the total cross-sectional area was calculated to estimate the fibrosis formation by using Northern Eclipse software (Empix Imaging Inc). The ratio of the fibrotic area within the injury sites was quantified using a previously described protocol.<sup>12,13,26,33</sup>

**Evaluation of MSTN Expression After Suramin Therapy.** To measure the MSTN expression in injured muscle, cryosectioned tissue was fixed in 4% formalin for 5 minutes followed by two 10-minute washes with PBS. The sections were then blocked with 10% HS for 1 hour at RT. Sections were incubated overnight at 4°C with primary antibodies (goat anti GDF-8 AF-788, R&D Systems Inc, Minneapolis, Minnesota) in 2% HS. After washing in PBS, samples were incubated with the secondary antibody (donkey anti-goat IgG conjugated with Alexa Fluor 555 [Invitrogen]) in 2% HS for 1 hour at RT.

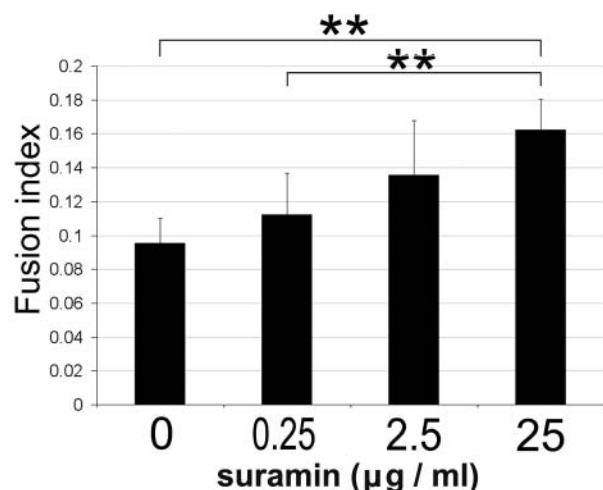
The total MSTN positive area was calculated using Northern Eclipse software (Empix Imaging Inc). The total positive area within the injury site was quantified using a previously described protocol.<sup>12,13,26,33</sup>

**Physiologic Evaluation of Muscle Contractile Properties After Suramin Therapy.** Contusion injuries were made on TA muscles of both legs of normal mice and treated as described above. Four weeks after injury, muscles from both legs were tested to evaluate peak twitch and tetanic force. Tibialis anterior muscles were harvested bilaterally, placed in a vertical chamber that was constantly perfused with mammalian Ringer solution aerated with 95% O<sub>2</sub>–5% CO<sub>2</sub> and maintained at 25°C. The distal attachment of the muscle was mounted to a glass tissue-support rod, and the proximal end of muscle on the tibia was connected to a force transducer and length servo system (Aurora Scientific, Aurora, Ontario, Canada). The muscles were stimulated by monophasic rectangular pulses of current (1 millisecond in duration) delivered through platinum electrodes placed 1 cm apart. The current was increased by 50% more than the current necessary to obtain peak force (250–300 mA) to ensure maximal stimulation. Using a micropositioner, muscles were first adjusted to their optimum length (Lo), defined as the length at which maximum isometric twitch tension was produced. Maximal tetanic force was assessed via a stimulation frequency of 75 Hz delivered in a 500-millisecond train. After the procedure, each muscle was weighed and specific peak twitch force and specific peak tetanic force were calculated and expressed in force per unit cross-sectional area (N/cm<sup>2</sup>).

## Statistical Analysis

All of the results from this study were expressed as the mean  $\pm$  standard deviation. The result of MSTN expression in vivo was analyzed using the *t* test and all the other results were statistically analyzed using analysis of variance. Differences among the groups were analyzed by using Scheffé multiple comparisons (post hoc test). Statistical significance was defined as *P* < .05.





**Figure 1.** Fusion index was measured to evaluate C2C12 myoblast differentiation stimulated by different concentration of suramin (0, 0.25, 2.5, and 25 µg/mL). \*\* $P < .01$ .

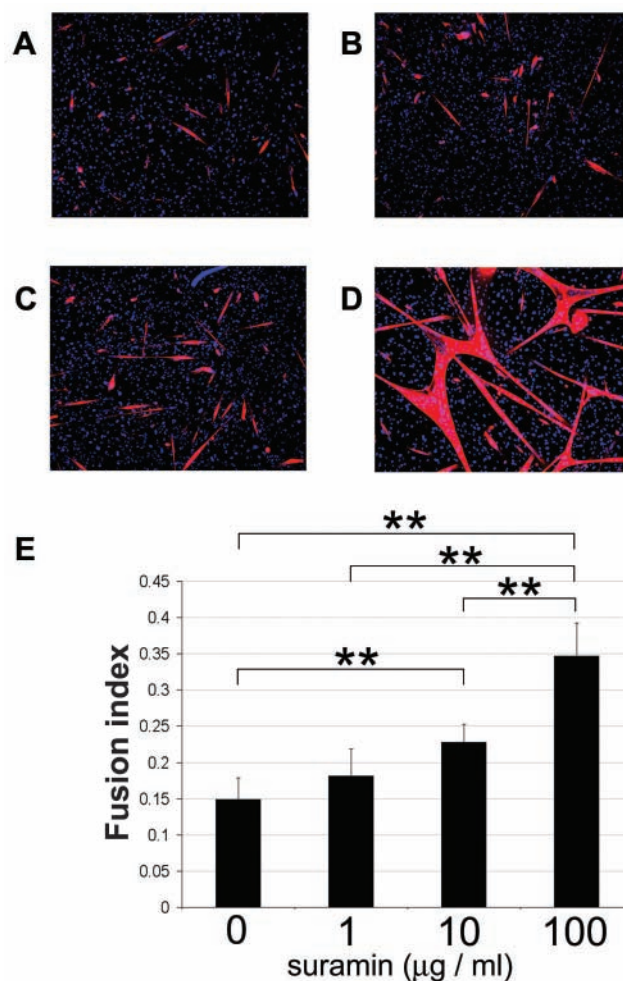
## RESULTS

### In Vitro Potential of Suramin to Induce Myogenic Differentiation

**Effect of Suramin on Myoblasts.** The effect of suramin on the differentiation of C2C12 cells is shown in Figure 1. The fusion index of C2C12 cells in the group treated with suramin (25 µg/mL) ( $0.162 \pm 0.018$ ) was significantly higher at 4 days of incubation as compared with the fusion index in the control group (0 µg/mL) ( $0.0953 \pm 0.015$ ). Moreover, the high-dose suramin-treated group (25 µg/mL) displayed a significantly higher fusion index than the low-dose suramin-treated group (0.25 µg/mL). The effect of suramin to induce the differentiation of C2C12 appeared to be dose-dependent.

**Effect of Suramin on MDSCs.** Suramin also stimulated MDSC differentiation in a dose-dependent manner (Figure 2E). Suramin-treated MDSCs enhanced the differentiation of MDSCs after 3 days of incubation. Suramin-treated groups (10 and 100 µg/mL) (Figures 2C and 2D) showed significantly higher fusion indexes ( $0.228 \pm 0.025$ ,  $0.347 \pm 0.0456$ ) than the control group (0 µg/mL) (Figure 2A) ( $0.149 \pm 0.030$ ). Among the suramin-treated groups, the high-dose suramin-treatment group (100 µg/mL) (Figure 2D) displayed a significantly higher fusion index when compared with the 2 lower-dose treatment groups (1 and 10 µg/mL) (Figures 2B and 2C).

**Ability of Suramin to Neutralize MSTN's Inhibition of MDSC Differentiation.** The group containing only MSTN (0 µg/mL suramin and 100 ng/mL MSTN) (Figure 3B) showed a significantly lower fusion index ( $0.091 \pm 0.020$ ) than the control group (0 µg/mL suramin and 0 ng/mL MSTN) (Figure 3A) ( $0.152 \pm 0.035$ ). All groups containing both suramin and MSTN (1, 10, and 100 µg/mL suramin and 100 ng/mL MSTN) (Figures 3C, 3D, and 3E) demonstrated significantly higher fusion indexes ( $0.153 \pm 0.035$ ,  $0.162 \pm 0.048$ ,  $0.279 \pm 0.041$ ) when compared with the

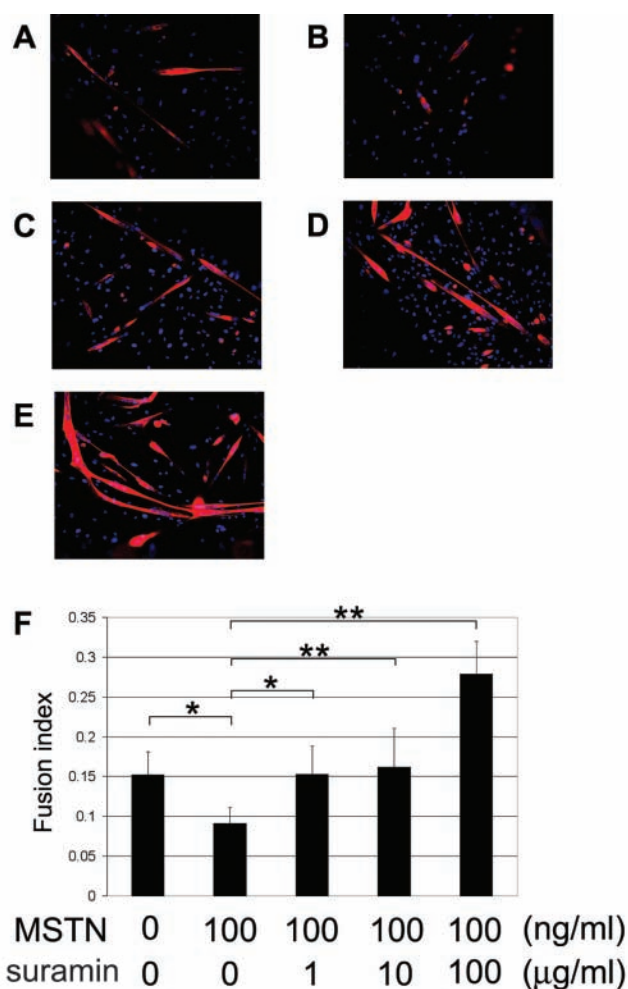


**Figure 2.** Immunocytochemical staining of muscle-derived stem cells (MDSCs) for fast myosin heavy chain at 3 days after incubation with different doses of suramin (A, 0 µg/mL; B, 1 µg/mL; C, 10 µg/mL; and D, 100 µg/mL). Myotubes are shown in red and nuclei are in blue (original magnification, ×200). E, comparison of fusion index of MDSC differentiation. \*\* $P < .01$ .

group containing only MSTN (Figure 3B). Suramin appeared to neutralize MSTN's inhibitory effect on MDSC differentiation and, moreover, appeared to stimulate the fusion of MDSCs in a dose-dependent manner (Figure 3F).

### Histologic and Physiologic Effects of Suramin on Muscle Healing After Contusion Injury In Vivo

**Effect of Suramin Treatment on Muscle Regeneration After Contusion Injury.** All the centronucleated regenerating myofibers present in the injured muscle were counted and compared among the groups (Figure 4E). The suramin-treated muscles displayed numerous regenerating myofibers at the contusion site. All the suramin-treated groups (2.5, 5, and 10 mg) (Figures 4B, 4C, and 4D) showed significantly higher numbers of regenerating myofibers ( $361.6 \pm 84.39$ ,  $341.1 \pm 57.21$ ,  $308.5 \pm 84.33$ )

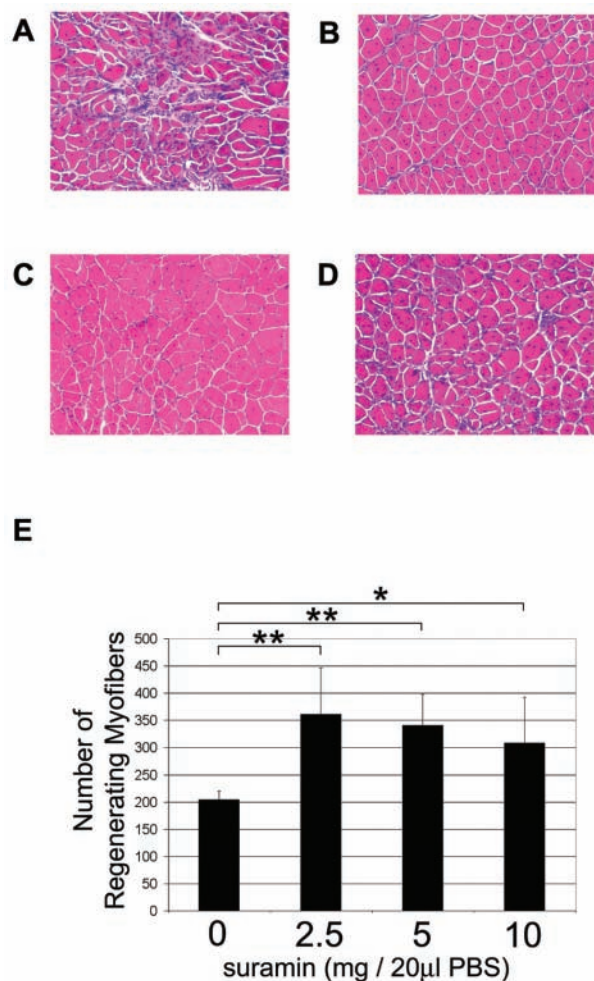


**Figure 3.** Immunocytochemical staining of muscle-derived stem cells (MDSCs) for fast myosin heavy chain at 3 days after incubation in 2% Dulbecco's modified Eagle's medium with different doses of suramin and myostatin (MSTN) (A, 0  $\mu\text{g}/\text{mL}$  suramin and 0  $\text{ng}/\text{mL}$  MSTN; B, 0  $\mu\text{g}/\text{mL}$  suramin and 100  $\text{ng}/\text{mL}$  MSTN; C, 1  $\mu\text{g}/\text{mL}$  suramin and 100  $\text{ng}/\text{mL}$  MSTN; D, 10  $\mu\text{g}/\text{mL}$  suramin and 100  $\text{ng}/\text{mL}$  MSTN; and E, 100  $\mu\text{g}/\text{mL}$  suramin and 100  $\text{ng}/\text{mL}$  MSTN). Myotubes are shown in red and nuclei are in blue (original magnification,  $\times 200$ ). F, comparison of fusion index of MDSC differentiation. \* $P < .05$ , \*\* $P < .01$ .

compared with the control group (0 mg of suramin) (Figure 4A) ( $204.6 \pm 15.27$ ).

**Effect of Suramin Therapy on Muscle Fibrosis After Contusion Injury.** After Masson trichrome staining, the area of fibrotic scar tissue was evaluated and compared among the groups (Figure 5E). All the suramin-treated groups (2.5, 5, and 10 mg) (Figures 5B, 5C, and 5D) showed significantly less fibrotic area ( $6.856 \pm 2.588$ ,  $7.677 \pm 2.897$ ,  $8.993 \pm 2.980$ ) compared with the untreated control group (0 mg of suramin) (Figure 5A) ( $19.109 \pm 3.215$ ).

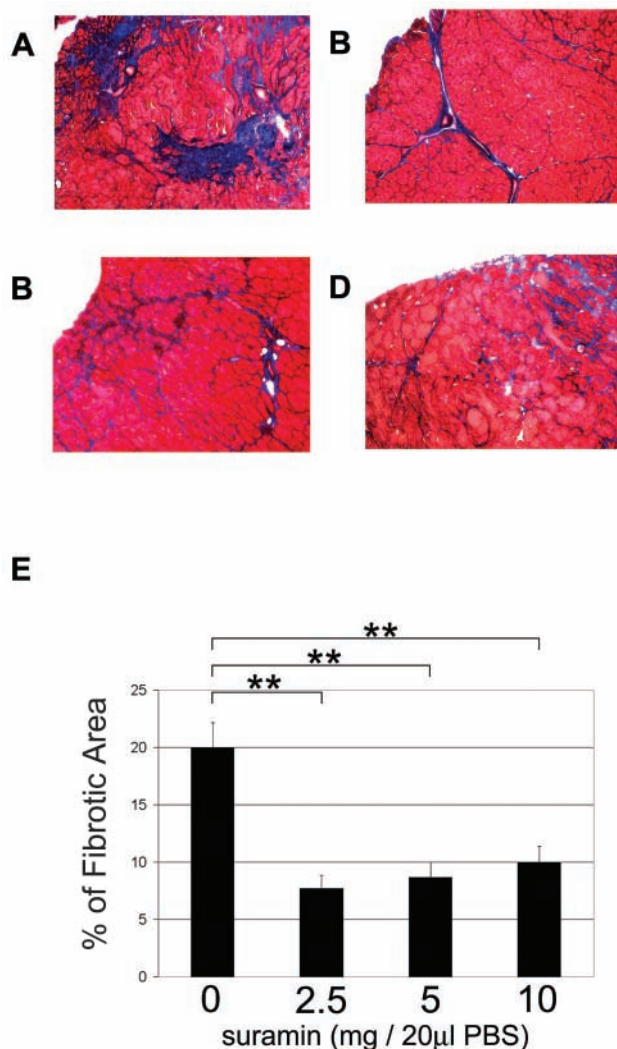
**Suramin Injection Downregulated MSTN Expression in Injured Muscle.** Immunohistochemical staining was performed to detect MSTN expression in the contusion-injured TA muscles. The MSTN-positive areas were



**Figure 4.** Histologic evaluation of muscle regeneration at four weeks after contusion injury by hematoxylin and eosin staining of tibialis anterior muscle treated with different concentrations of suramin (A, 0 mg/20  $\mu\text{L}$  phosphate-buffered saline [PBS]; B, 2.5 mg/20  $\mu\text{L}$  PBS; C, 5 mg/20  $\mu\text{L}$  PBS; and D, 10 mg/20  $\mu\text{L}$  PBS) injected at 2 weeks after injury. Regenerating myofibers were defined by centronucleated myofibers (original magnification,  $\times 100$ ). E, quantification of the number of regenerating myofibers treated with various concentrations of suramin. \* $P < .05$ , \*\* $P < .01$ .

measured and compared between the various treatment groups (Figure 6C). The muscle treated with 2.5-mg suramin injection 2 weeks after injury showed significantly less MSTN expression ( $4466.7 \pm 7306.1$ ) when compared with the untreated control (0 mg suramin) ( $27830.2 \pm 23206.3$ ) (Figures 6A and 6B).

**Suramin Injection Improved Muscle Strength After Contusion Injury.** The results of the physiologic evaluations are shown in Table 1. The control group (0 mg of suramin) and all the suramin-treatment groups, with the exception of the 2.5-mg suramin-treatment group, showed significantly less specific peak force (twitch and tetanic) when compared with the normal noninjured group. On the other hand, the muscles treated with 2.5 mg of suramin

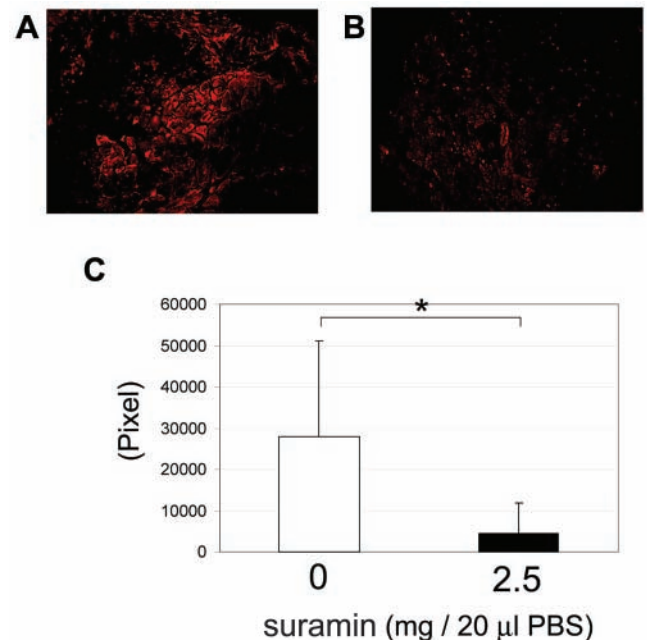


**Figure 5.** Histologic evaluation of the formation of scar tissue at 4 weeks after contusion injury by Masson trichrome staining of tibialis anterior muscle treated with different concentrations of suramin (A, 0 mg/20 µL phosphate-buffered saline [PBS]; B, 2.5 mg/20 µL PBS; C, 5 mg/20 µL PBS; and D, 10 mg/20 µL PBS) injected at 2 weeks after injury. Scar tissues are shown in blue and muscles are in red (original magnification,  $\times 100$ ). E, quantification of the scar tissue area in tibialis anterior muscle treated with various concentrations of suramin.  $**P < .01$ .

showed significantly greater specific peak force (twitch and tetanic) than the untreated control group. There was no significant difference between injured muscle that had been treated with 2.5 mg of suramin and normal noninjured muscle. In addition, the muscles injected with 2.5 mg of suramin also showed significantly greater specific peak tetanic force than the other suramin-treated groups (5 and 10 mg) and the control group (0 mg of suramin).

## DISCUSSION

The aim of this study was to evaluate the effect of suramin on myogenic cell differentiation and muscle healing after



**Figure 6.** Immunohistochemical staining for MSTN at 2 days after suramin injection 2 weeks after injury (A, 0 mg suramin/20 µL phosphate-buffered saline [PBS]; B, 2.5 mg suramin/20 µL PBS). C, quantification of the total MSTN-positive area treated with suramin.  $*P < .05$ .

**TABLE 1**  
Results of Specific Peak Twitch and Titanic Force

Group	Specific Peak Twitch Force (N/cm <sup>2</sup> )	Specific Peak Titanic Force (N/cm <sup>2</sup> )
Normal (noninjured)	7.728 ± 0.312 <sup>a</sup>	23.272 ± 1.334 <sup>a</sup>
0 mg suramin	4.431 ± 0.903	13.797 ± 2.136
2.5 mg suramin	6.305 ± 1.239 <sup>b</sup>	21.055 ± 2.662 <sup>a</sup>
5 mg suramin	5.014 ± 0.337	15.131 ± 0.830
10 mg suramin	4.993 ± 1.074	15.085 ± 2.792

<sup>a</sup> $P < .01$  compared with 0, 5, and 10 mg suramin groups.

<sup>b</sup> $P < .05$  compared with 0 mg suramin group.

contusion injury. We hypothesized that suramin treatment would lead to better biological healing by both stimulating muscle regeneration and preventing fibrosis in contused muscle. Histologically, the muscle treated with suramin 2 weeks after injury showed more regenerating myofibers and less fibrotic scar formation when compared with the control group (0 mg of suramin) at 4 weeks after contusion injury. Furthermore, suramin treatment also showed an increase in muscle strength compared with the untreated control group.

The muscle contusion injuries we modeled in this study are among the most common muscle injuries encountered in contact sports and by military personnel. More than



90% of muscle injuries are caused either by contusion or by excessive strain of the muscle.<sup>3,14</sup> Although contusion injury is capable of healing, incomplete functional recovery often occurs, depending on the severity of the initial trauma. Skeletal muscle has a great regenerative potential,<sup>†</sup> largely attributed to the activation of muscle progenitor cells and their fusion into mature multinucleated myofibers<sup>22,40,41</sup>; however, scar tissue formation occurs simultaneously and likely competes with muscle regeneration during the muscle-healing process.<sup>12,26,32</sup>

We have investigated the effect of some treatments, such as suture or immobilization, which are normally used in the clinic for muscle injury, by using animal models. One study showed that immobilization after muscle laceration had no significant effect on fibrosis reduction. Suture repair promoted better healing of the injured muscle and prevented the development of fibrosis at the deep-tissue level, but not superficially.<sup>33</sup>

Suramin, which is a polysulphonated naphthylurea, was designed as an antiparasitic drug<sup>18</sup> and is used for the treatment of human sleeping sickness, onchocerciasis, and other diseases caused by trypanosomes and other worms. In addition, it is under investigation as a treatment for some malignancies such as prostate, adrenal cortex, lymphoma, breast, and colon cancers<sup>49</sup> and for human immunodeficiency virus-1.<sup>29</sup> The major systemic side effects of suramin are malaise, neuropathy,<sup>2,7</sup> mineral corticoid insufficiency,<sup>27</sup> and corneal deposits<sup>19</sup>; occasionally neutropenia,<sup>9</sup> thrombocytopenia,<sup>47</sup> and renal failure<sup>42</sup> have also been observed. The toxicity of suramin when injected intramuscularly, as we did in our animal model, has not yet been determined. Although we observed no adverse effects in the mice injected with up to 10 mg of suramin in this study, we did not specifically test to evaluate side effects. Suramin is known as a heparin analog that can bind to heparin-binding proteins and inhibit the effect of growth factors by competitively binding to growth factor receptors.<sup>43,49</sup> Transforming growth factor- $\beta$ 1, - $\beta$ 2, and - $\beta$ 3; platelet-derived growth factor (PDGF) A and B; and epidermal growth factor are growth factors that are known to be inhibited by suramin. Among them, TGF- $\beta$ 1 and - $\beta$ 2 and PDGF A and B are known to have the potential to promote fibroblast proliferation.<sup>44,46</sup>

In our *in vivo* study using the muscle-contusion model, direct injection of suramin at 2 weeks after muscle injury demonstrated a significant reduction of fibrous tissue formation when compared with the untreated control (0 mg of suramin). We found that suramin treatment led to a beneficial effect in contused muscle, as was previously seen in suramin-treated lacerations and strains<sup>5,6</sup> as well as when using other antifibrotic agents such as decorin and interferon gamma.<sup>12,13</sup> Moreover, our *in vivo* results indicate that 2.5 mg of suramin was the optimal dosage for the treatment of muscle contusions as there was no significant difference observed when higher dosages (5 and 10 mg) of suramin was injected into the injury site. Our previous work with the laceration and strain models compared doses that were different than the current study and we have difficulty making direct comparisons between the

current study and the former studies. In the laceration study, we compared suramin doses at 0.25, 1.0, and 2.5 mg and found that the 2.5-mg dose was optimal.<sup>6</sup> In the strain model study, we compared doses at 0.25, 1.0, and 5 mg and found that the 5-mg dose was optimal.<sup>5</sup> Because we did not use a 2.5-mg dose in the strain study and did not use a 5-mg dose in the laceration study, we cannot definitively say that the 2.5-mg dosage would be optimal for these types of injuries, although it is strongly inferred.

This study also showed that suramin enhanced muscle regeneration when it was injected directly into the muscle 2 weeks after receiving a contusion injury. We found many regenerating myofibers at the injury site, usually sequestered by a large amount of fibrotic tissue. All the suramin-treated groups showed a significant increase in the number of regenerating myofibers at 4 weeks after receiving the injury.

Functional recovery after muscle injury is the most important variable determining the likelihood for clinical translation of this therapy in the treatment of skeletal muscle injury. As was observed with other antifibrotic agents (decorin and interferon gamma),<sup>12,13</sup> suramin also appears to have a beneficial effect on the physiologic recovery of skeletal muscle. Our results showed that there was no significant difference in the specific peak twitch and tetanic forces between normal noninjured muscle and contused 2.5-mg suramin-treated muscle. These results strongly indicate that the injection of 2.5 mg of suramin at 2 weeks after contusion injury can improve muscle strength and promote functional recovery after muscle injury.

Taken together, our *in vitro* study about the effect of suramin on myogenic cell differentiation provides insight as to the underlying mechanism by which suramin enhances muscle regeneration *in vivo*. Our *in vitro* results showed 25  $\mu$ g/mL of suramin can significantly enhance C2C12 differentiation at 4 days after incubation and, in addition, suramin treatment leads to significant increases in the fusion index in a dose-dependent manner. Further, we observed an even more prominent dose-dependent effect on MDSC differentiation 3 days after initiating the incubation with suramin. Moreover, suramin also showed a neutralizing effect on MSTN, which inhibits differentiation of MDSCs in a dose-dependent manner.

We found that suramin stimulates myogenic differentiation *in vitro*. It is consistent with our *in vivo* results, showing that suramin is capable of enhancing muscle regeneration and improving muscle healing after muscle injury. Furthermore, as expected, we observed that MSTN significantly inhibits the myogenic differentiation of MDSCs; however, in the presence of suramin, the inhibitory effect of MSTN on myogenic differentiation was attenuated in a dose-dependent manner. These results suggest that suramin can neutralize MSTN activity. Therefore, we hypothesize that when myoblasts and MDSCs are treated with suramin, suramin stimulates myogenic differentiation by neutralizing the effect of endogenous MSTN. A similar neutralizing effect on MSTN has been seen when cells were treated with decorin, a TGF- $\beta$ 1 blocker.<sup>48</sup>

<sup>†</sup>References 4, 14, 16, 21, 26, 28, 33, 45



On the basis of these results, we further investigated whether suramin exerts a beneficial effect in the injured muscle through regulating MSTN expression. Not surprisingly, it was revealed that treatment with suramin significantly decreased MSTN expression in the injured muscle. Our previous study showed that MSTN can act with TGF- $\beta$ 1 to magnify fibrosis cascades in injured muscles.<sup>48</sup> Taken together, it may suggest that suramin administration effectively leads to enhanced muscle regeneration and reduced fibrosis after muscle injury via downregulation of endogenous MSTN.

This is the first study conducted to evaluate the effects that suramin would have on a contusion injury. It is also the first study to demonstrate that one of the mechanisms by which suramin could enhance skeletal muscle healing was by the downregulation of MSTN. Our results showed suramin can enhance myogenic cell differentiation and neutralize the effects of MSTN, which downregulates MDSC differentiation. Moreover, these in vitro results may reveal a possible mechanism by which suramin directly enhances muscle regeneration after muscle injury. Future studies should investigate further the mechanism by which suramin appears to stimulate myogenic differentiation and promotes muscle healing via MSTN regulation.

In summary, we demonstrated that the direct injection of suramin at 2 weeks after contusion injury can effectively reduce fibrotic scar formation and enhance muscle regeneration 4 weeks after injury. Physiologic evaluation also showed that suramin can enhance muscle functional recovery after contusion injury. Our in vitro study demonstrated that culturing either C2C12 myoblasts or MDSCs with suramin led to a significant increase in the fusion index of the cells. Moreover, with the addition of both suramin and MSTN in cell cultures, suramin was able to counteract MSTN's biological activity, thereby rescuing MSTN-inhibited myogenic differentiation of MDSCs.

The greatest advantage of using suramin is that this drug has already been approved by the FDA.<sup>34,39</sup> Future studies should consider the use of this agent for off-label use in the treatment of skeletal muscle injuries. Our findings could contribute to the development of progressive therapies for treating skeletal muscle injuries.

## ACKNOWLEDGMENT

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## REFERENCES

1. Alameddine HS, Dehaupas M, Fardeau M. Regeneration of skeletal muscle fibers from autologous satellite cells multiplied in vitro: an experimental model for testing cultured cell myogenicity. *Muscle Nerve*. 1989;12:544-555.

2. Bitton RJ, Figg WD, Venzon DJ, et al. Pharmacologic variables associated with the development of neurologic toxicity in patients treated with suramin. *J Clin Oncol*. 1995;13:2223-2229.
3. Canale ST, Cantler ED Jr, Sisk TD, Freeman BL. A chronicle of injuries of an American intercollegiate football team. *Am J Sports Med*. 1981;9:384-389.
4. Carlson BM, Faulkner JA. The regeneration of skeletal muscle fibers following injury: a review. *Med Sci Sports Exerc*. 1983;15:187-198.
5. Chan YS, Li Y, Foster W, Fu FH, Huard J. The use of suramin, an antifibrotic agent, to improve muscle recovery after strain injury. *Am J Sports Med*. 2005;33:43-51.
6. Chan YS, Li Y, Foster W, et al. Antifibrotic effects of suramin in injured skeletal muscle after laceration. *J Appl Physiol*. 2003;95:771-780.
7. Chaudry V, Eisenberger MA, Sinibaldi VJ, Sheikh H, Griffin JW, Cornblath DR. A prospective study of suramin induced peripheral neuropathy. *Brain*. 1996;119:2039-2052.
8. Crisco JJ, Jokl P, Heinen GT, Connell MD, Panjabi MM. A muscle contusion injury model: biomechanics, physiology, and histology. *Am J Sports Med*. 1994;22:702-710.
9. Dawson NA, Lush RM, Steinberg SM, Tompkins AC, Headlee DJ, Figg WD. Suramin-induced neutropenia. *Eur J Cancer*. 1996;32A:1534-1539.
10. Diaz JA, Fischer DA, Rettig AC, Davis TJ, Shelbourne KD. Severe quadriceps muscle contusions in athletes: a report of three cases. *Am J Sports Med*. 2003;31:289-293.
11. Fischman DA. The synthesis and assembly of myofibrils in embryonic muscle. *Curr Top Dev Biol*. 1970;5:235-280.
12. Foster W, Li Y, Usas A, Somogyi G, Huard J. Gamma interferon as an antifibrosis agent in skeletal muscle. *J Orthop Res*. 2003;21:798-804.
13. Fukushima K, Badlani N, Usas A, Riano F, Fu F, Huard J. The use of an antifibrosis agent to improve muscle recovery after laceration. *Am J Sports Med*. 2001;29:394-402.
14. Garrett WE Jr. Muscle strain injuries: clinical and basic aspects. *Med Sci Sports Exerc*. 1990;22:436-443.
15. Garrett WE Jr, Safran MR, Seaber AV, Glisson RR, Ribbeck BM. Biomechanical comparison of stimulated and nonstimulated skeletal muscle pulled to failure. *Am J Sports Med*. 1987;15:448-454.
16. Garrett WE Jr, Seaber AV, Boswick J, Urbaniak JR, Goldner JL. Recovery of skeletal muscle after laceration and repair. *J Hand Surg [Am]*. 1984;9:683-692.
17. Grounds MD. Towards understanding skeletal muscle regeneration. *Pathol Res Pract*. 1991;187:1-22.
18. Hawking F. Suramin: with special reference to onchocerciasis. *Adv Pharmacol Chemother*. 1978;15:289-322.
19. Hemady RK, Sinibaldi VJ, Eisenberger MA. Ocular symptoms and signs associated with suramin sodium treatment for metastatic cancer of the prostate. *Am J Ophthalmol*. 1996;121:291-296.
20. Honda H, Kimura H, Rostami A. Demonstration and phenotypic characterization of resident macrophages in rat skeletal muscle. *Immunology*. 1990;70:272-277.
21. Hughes C 4th, Hasselman CT, Best TM, Martinez S, Garrett WE Jr. Incomplete, intrasubstance strain injuries of the rectus femoris muscle. *Am J Sports Med*. 1995;23:500-506.
22. Hurme T, Kalimo H. Activation of myogenic precursor cells after muscle injury. *Med Sci Sports Exerc*. 1992;24:197-205.
23. Hurme T, Kalimo H, Lehto M, Jarvinen M. Healing of skeletal muscle injury: an ultrastructural and immunohistochemical study. *Med Sci Sports Exerc*. 1991;23:801-810.
24. Jackson DW, Feagin JA. Quadriceps contusions in young athletes: relation of severity of injury to treatment and prognosis. *J Bone Joint Surg Am*. 1973;55:95-105.
25. Jarvinen MJ, Lehto MU. The effects of early mobilisation and immobilisation on the healing process following muscle injuries. *Sports Med*. 1993;15:78-89.
26. Kasemkijwattana C, Menetrey J, Somogyi G, et al. Development of approaches to improve the healing following muscle contusion. *Cell Transplant*. 1998;7:585-598.

27. Kobayashi K, Weiss RE, Vogelzang NJ, Vokes EE, Janisch L, Ratain MJ. Mineralocorticoid insufficiency due to suramin therapy. *Cancer*. 1996;78:2411-2420.
28. Lefaucheur JP, Sebille A. Muscle regeneration following injury can be modified in vivo by immune neutralization of basic fibroblast growth factor, transforming growth factor beta 1 or insulin-like growth factor I. *J Neuroimmunol*. 1995;57:85-91.
29. Levine AM, Gill PS, Cohen J, et al. Suramin antiviral therapy in the acquired immunodeficiency syndrome: clinical, immunological, and virologic results. *Ann Intern Med*. 1986;105:32-37.
30. Li Y, Foster W, Deasy BM, et al. Transforming growth factor-beta1 induces the differentiation of myogenic cells into fibrotic cells in injured skeletal muscle: a key event in muscle fibrogenesis. *Am J Pathol*. 2004;164:1007-1019.
31. Li Y, Huard J. Differentiation of muscle-derived cells into myofibroblasts in injured skeletal muscle. *Am J Pathol*. 2002;161:895-907.
32. Menetrey J, Kasemkijwattana C, Day CS, et al. Growth factors improve muscle healing in vivo. *J Bone Joint Surg Br*. 2000;82:131-137.
33. Menetrey J, Kasemkijwattana C, Fu FH, Moreland MS, Huard J. Suturing versus immobilization of a muscle laceration: a morphological and functional study in a mouse model. *Am J Sports Med*. 1999;27:222-229.
34. Mietz H, Chevez-Barrios P, Feldman RM, Lieberman MW. Suramin inhibits wound healing following filtering procedures for glaucoma. *Br J Ophthalmol*. 1998;82:816-820.
35. Qu Z, Balkir L, van Deutekom JC, Robbins PD, Pruchnic R, Huard J. Development of approaches to improve cell survival in myoblast transfer therapy. *J Cell Biol*. 1998;142:1257-1267.
36. Rando TA, Blau HM. Primary mouse myoblast purification, characterization, and transplantation for cell-mediated gene therapy. *J Cell Biol*. 1994;125:1275-1287.
37. Reznik M, Engel WK. Ultrastructural and histochemical correlations of experimental muscle regeneration. *J Neurol Sci*. 1970;11:167-185.
38. Ryan JB, Wheeler JH, Hopkinson WJ, Arciero RA, Kolakowski KR. Quadriceps contusions: West Point update. *Am J Sports Med*. 1991;19:299-304.
39. Schrell UM, Gauer S, Kiesewetter F, et al. Inhibition of proliferation of human cerebral meningioma cells by suramin: effects on cell growth, cell cycle phases, extracellular growth factors, and PDGF-BB autocrine growth loop. *J Neurosurg*. 1995;82:600-607.
40. Schultz E. Satellite cell behavior during skeletal muscle growth and regeneration. *Med Sci Sports Exerc*. 1989;21(5 Suppl):S181-186.
41. Schultz E, Jaryszak DL, Valliere CR. Response of satellite cells to focal skeletal muscle injury. *Muscle Nerve*. 1985;8:217-222.
42. Smith A, Harbour D, Liebmann J. Acute renal failure in a patient receiving treatment with suramin. *Am J Clin Oncol*. 1997;20:433-434.
43. Stein CA. Suramin: a novel antineoplastic agent with multiple potential mechanisms of action. *Cancer Res*. 1993;53(10 Suppl):2239-2248.
44. Sullivan KM, Lorenz HP, Meuli M, Lin RY, Adzick NS. A model of scarless human fetal wound repair is deficient in transforming growth factor beta. *J Pediatr Surg*. 1995;30:198-202.
45. Taylor DC, Dalton JD Jr, Seaber AV, Garrett WE Jr. Experimental muscle strain injury: early functional and structural deficits and the increased risk for reinjury. *Am J Sports Med*. 1993;21:190-194.
46. Thomas DW, O'Neill ID, Harding KG, Shepherd JP. Cutaneous wound healing: a current perspective. *J Oral Maxillofac Surg*. 1995;53:442-447.
47. Tisdale JF, Figg WD, Reed E, McCall NA, Alkins BR, Horne MK 3rd. Severe thrombocytopenia in patients treated with suramin: evidence for an immune mechanism in one. *Am J Hematol*. 1996;51:152-157.
48. Zhu J, Li Y, Shen W, et al. Relationships between transforming growth factor-beta1, myostatin, and decorin: implications for skeletal muscle fibrosis. *J Biol Chem*. 2007;282:25852-25863.
49. Zumkeller W, Schofield PN. Growth factors, cytokines and soluble forms of receptor molecules in cancer patients. *Anticancer Res*. 1995;15:343-348.

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# Angiotensin II Receptor Blockade Administered After Injury Improves Muscle Regeneration and Decreases Fibrosis in Normal Skeletal Muscle

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**Background:** Several therapeutic agents have been shown to inhibit fibrosis and improve regeneration after injury in skeletal muscle by antagonizing transforming growth factor- $\beta$ 1. Angiotensin receptor blockers have been shown to have a similar effect on transforming growth factor- $\beta$ 1 in a variety of tissues.

**Hypothesis:** Systemic treatment of animals after injury of skeletal muscle with an angiotensin receptor blocker may decrease fibrosis and improve regeneration, mainly through transforming growth factor- $\beta$ 1 blockade, and can be used to improve skeletal muscle healing after injury.

**Study Design:** Controlled laboratory study.

**Methods:** Forty mice underwent bilateral partial gastrocnemius lacerations. Mice were assigned randomly to a control group (tap water), a low-dose angiotensin receptor blocker group (losartan, 0.05 mg/mL), or a high-dose angiotensin receptor blocker group (0.5 mg/mL). The medication was dissolved in tap water and administered enterally. Mice were sacrificed 3 or 5 weeks after injury, and the lacerated muscles were examined histologically for muscle regeneration and fibrosis.

**Results:** Compared with control mice at 3 and 5 weeks, angiotensin receptor blocker-treated mice exhibited a histologic dose-dependent improvement in muscle regeneration and a measurable reduction in fibrous tissue formation within the area of injury.

**Conclusion:** By modulating the response to local and systemic angiotensin II, angiotensin receptor blocker therapy significantly reduced fibrosis and led to an increase in the number of regenerating myofibers in acutely injured skeletal muscle. The clinical implications for this application of angiotensin receptor blockers are potentially far-reaching and include not only sports- and military-related injuries, but also diseases such as the muscular dystrophies and trauma- and surgery-related injury.

**Clinical Relevance:** Angiotensin receptor blockers may provide a safe, clinically available treatment for improving healing after skeletal muscle injury.

**Keywords:** fibrosis; angiotensin receptor blocker; TGF- $\beta$ ; muscle injury; muscle regeneration

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Skeletal muscle injuries are among the most common complaints of patients seen by general medical physicians and also account for a large majority of patients seen in orthopaedic clinics.<sup>2</sup> Investigations have demonstrated that the natural history of muscle injury proceeds through a

highly coordinated sequence of steps. Unfortunately, the regenerative capacity of injured skeletal muscle is limited; fibrotic tissue is a common end result that predisposes the muscle to recurrent injury and limits recovery of function.<sup>16</sup> Clinical experience reveals a high recurrence rate of skeletal muscle strain injuries among athletes, approaching 30% in some professional-level athletes.<sup>32</sup> Advancements in the identification of molecular events and cellular transformations after muscle injury have flourished; however, the clinical treatment of this common condition still relies on conventional therapies of rest, ice, and anti-inflammatory medications; these are of limited efficacy in preventing or

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No potential conflict of interest declared.

treating posttraumatic muscle fibrosis and in reducing the rate of reinjury.<sup>1,18,33</sup>

In our laboratory, we have investigated several biological agents that have proved to be of some benefit in altering the natural course of muscle injury. Specifically, we have focused our recent efforts on agents that inhibit muscle fibrosis via inhibition of transforming growth factor- $\beta$ 1 (TGF- $\beta$ 1), a key cytokine in the fibrotic signaling pathway in skeletal muscle.<sup>21</sup> Using decorin, suramin, relaxin, and gamma interferon, we have demonstrated that these therapies can decrease fibrosis and increase regeneration after skeletal muscle injury.<sup>9,13,14,22,24</sup> However, their use clinically is hampered by relatively severe side-effect profiles, lack of oral dosing formulations, and in some cases, lack of Food and Drug Administration (FDA) approval for use in humans.

Fibrosis is a pathologic process that is not unique to the skeletal muscle system. Observations have linked pathologic fibrosis in various organ systems to the local effects of a naturally occurring molecule, angiotensin II, an end product of the blood pressure-regulating renin-angiotensin system. The modulation of angiotensin II with angiotensin-converting enzyme inhibitors or angiotensin II receptor blockers has demonstrated decreased fibrosis and improved function in liver, kidney, and lung tissue.<sup>23,27,28,30</sup> Injured cardiac muscle in disease entities such as congestive heart failure also demonstrates dysfunction related to fibrosis. Myocardium exposed to decreased levels of angiotensin II, either through the use of angiotensin-converting enzyme inhibitors or angiotensin receptor blockers (ARB), has also demonstrated measurably improved function.<sup>15,31</sup> Investigators have also observed a relationship between the modulation of angiotensin II and skeletal muscle. Patients treated with angiotensin-modulating medications for hypertension also displayed the unexpected side effect of decreased rates of muscle wasting and a reduction in the relative amount of adipose tissue within their musculature.<sup>25</sup> Moreover, elite athletes, particularly those in endurance sports, have also demonstrated findings consistent with inherent differences in their body's metabolism of angiotensin II, with decreased exposure resulting in improved skeletal muscle function.<sup>25</sup> We have observed an improvement in skeletal muscle regeneration postinjury after treatment with angiotensin blockade; this is a finding that, to our knowledge, had not been reported previously.<sup>4</sup> Elegant experiments have subsequently been reported that elucidate the mechanism by which angiotensin II receptor blockade modulates TGF- $\beta$ 1, which has also been implicated in the prevention of muscle regeneration in murine models of chronic myopathic disease.<sup>10</sup> The hypothesis of this study is that systemic delivery of an angiotensin II receptor blocker can enhance muscle regeneration and decrease fibrosis in a laceration model of normal skeletal muscle injury. This therapy may be an effective treatment when instituted postinjury, which is a clinically relevant scenario for physicians treating muscle injuries.

## MATERIALS AND METHODS

### In Vitro

The role of angiotensin II regarding myoblast and fibroblast proliferation was investigated using a series of standard

proliferation experiments. National Institutes of Health (NIH) 3T3 cells (fibroblast cell line) and C2C12 myoblasts, purchased from American Type Culture Collection (ATCC) (Rockville, Maryland), along with primary muscle fibroblast isolates (PP2 cells) obtained through the previously published preplating technique, were chosen for analysis.<sup>29</sup> These cells were cultured with Dulbecco's modified Eagle's medium (DMEM) (Invitrogen, Carlsbad, California) containing 10% fetal bovine serum, 10% horse serum, 0.5% chicken embryo extract, and 1% penicillin/streptomycin. All cells were cultured at 37°C in 5% CO<sub>2</sub>. National Institutes of Health 3T3, C2C12, and PP2 cells were seeded onto different 6-well plates. Cells were cultured with medium (described above) and 0, 10<sup>-8</sup>, 10<sup>-6</sup>, or 10<sup>-4</sup> mol/L of human angiotensin II (Sigma Chemical, St Louis, Missouri). Cell counts were performed at 24, 48, and 96 hours using a standard cell-counting chamber.

The supernatant solution from the PP2 cell culture was extracted after 24 and 48 hours of exposure to the various concentrations of angiotensin II. An enzyme-linked immunosorbent assay (ELISA) was performed in accordance with the manufacturer's recommendations (Sigma Chemical) to determine the level of TGF- $\beta$ 1 in the solution. National Institutes of Health 3T3 cells were harvested 48 hours after incubation with or without angiotensin II, and a western blot was performed. After lysis, the samples were separated by 12% sodium dodecyl sulfate-polyacrylamide gel electrophoresis and transferred to nitrocellulose membranes used for immunostaining. Mouse anti-TGF- $\beta$ 1 type I antibodies (Sigma Chemical) were then applied. The horseradish peroxidase-conjugated secondary antibodies (Pierce, Rockford, Illinois) were developed using SuperSignal West Pico Chemiluminescent substrate (Pierce), and positive bands were visualized on radiographic film. All results were analyzed using Northern Eclipse software v.6.0 (Empix Imaging, Mississauga, Ontario, Canada).

### Animal Model

Forty immunocompetent mice (C57Bl/6J; Jackson Laboratory, Bar Harbor, Maine) were used for the histologic analysis. The animals were housed in cages and fed with commercial pellets. The policies and procedures of the animal laboratory were in accordance with those detailed by the US Department of Health and Human Services and the Animal Research Care Committee of the authors' institution (Protocol #25-03). A previously reported muscle laceration injury model was employed for these experiments, the healing process of which is similar histologically to strain injury models, which account for the most common clinical pattern of injury.<sup>9,14,17,19,21</sup> The mice were anesthetized with 16  $\mu$ L of ketamine and 8  $\mu$ L of xylazine in 25  $\mu$ L of phosphate-buffered saline by intraperitoneal injection. For histologic analysis, lacerations were performed bilaterally on the gastrocnemius muscle through 50% of its width and 100% of its thickness at 60% of its length from its insertion. All mice were randomly assigned to 1 of 3 groups: (i) a control group, (ii) a low-dose ARB group, or (iii) a high-dose ARB group. The control group was fed tap water, while the low and high-dose ARB groups were fed commercially available losartan (Cozaar; Merck & Co, West Point,



Pennsylvania) dissolved in tap water at concentrations of 0.05 g/L, and 0.5 g/L, respectively. These doses were calculated based on the average fluid intake of a population of mice with similar demographic backgrounds to those tested in this study, and are well below reported toxicity levels. All animals were caged separately and allowed access to the water or ARB solutions ad libitum from the time of injury to the time of sacrifice. The animals were not pretreated in any way. The average daily fluid intake of each animal was monitored and recorded. Mice were sacrificed at 3 and 5 weeks. The injured muscles were isolated, mounted, and snap-frozen in liquid nitrogen-cooled 2-methylbutane. Samples were serially sectioned at 10  $\mu$ m with a cryostat for histologic analysis.

### Angiotensin Receptors in Skeletal Muscle

Immunohistochemistry was used to evaluate the presence and distribution of angiotensin II receptors in injured and uninjured skeletal muscle. Commercially available antibodies (Abcam Inc, Cambridge, Massachusetts) were used to localize angiotensin II receptors in skeletal muscle. The same sections were also stained with collagen IV antibodies (Biodesign International, Saco, Maine), which stain the extracellular matrix (basal lamina) of muscle fibers, and 4'-6-diamidino-2-phenylindole (DAPI) to delineate nuclear location. A blinded observer performed all analyses.

### Muscle Fibrosis

To detect the amount of fibrosis in the area of injury, sections from each limb of each animal were washed in deionized water and stained with a Masson Modified IMEB Trichrome Stain Kit (IMEB Inc, San Marcos, California) according to the manufacturer's specifications. This technique, which stains nuclei black, muscle red, and collagen blue, was previously validated through immunohistochemistry as an accurate technique for evaluating fibrous tissue within skeletal muscle.<sup>6,13,20</sup> Five randomly selected 200 $\times$  high-powered image fields within the injured area for each limb were obtained using a Nikon Eclipse 800 light microscope (Tokyo, Japan) fitted with a Spot-RT digital camera (Diagnostic Instruments, Sterling Heights, Michigan). Images were analyzed using Northern Eclipse image analysis software (Empix Imaging) to measure the percent area of collagen (blue staining tissue) within the injury zone. Color threshold levels within the software program were set to isolate the blue staining regions and calculate the area of that region that corresponded to the area of fibrosis. This value was expressed as a percentage of the entire cross-sectional area of the muscle section. A blinded observer performed all analyses.

### Muscle Regeneration

Muscle sections were stained with hematoxylin and eosin. Muscle regeneration was assessed by counting the number of centronucleated myofibers. Five 200 $\times$  high-powered fields throughout the injury zone were analyzed from each muscle, and the average number of regenerating myofibers per field was calculated. A blinded observer performed all analyses.

TABLE 1  
Varying Concentrations of Angiotensin II With Myoblast (C2C12) and Fibroblast (3T3, PP2) Cell Lines Did Not Affect Proliferation at 24, 48, or 72 Hours<sup>a</sup>

Concentrations, M	24 h	48 h	72 h
C2C12			
0	125	114	160
10 <sup>-8</sup>	145	135	150
10 <sup>-6</sup>	130	140	200
10 <sup>-4</sup>	110	135	140
PP2			
0	25	25.5	40
10 <sup>-8</sup>	30	21.5	65.5
10 <sup>-6</sup>	25	24.5	37.5
10 <sup>-4</sup>	22	24.5	34.5
3T3			
0	102.5	570	1205
10 <sup>-8</sup>	111.5	611.5	1144
10 <sup>-6</sup>	124.25	612.5	1158
10 <sup>-4</sup>	141.875	139.8	112.7

<sup>a</sup>Angiotensin II concentration is expressed in molar amounts, and cell counts are expressed as thousands of cells ( $\times 10^3$  cells).

### Statistical Methods

Comparisons of muscle fibrotic area and number of regenerating myofibers data were performed by means of a 2-way analysis of variance (ANOVA) and Tukey's post-hoc test using SPSS software, version 16.0 (SPSS Inc, Chicago, Illinois). Immunohistochemical data are presented and compared qualitatively.

## RESULTS

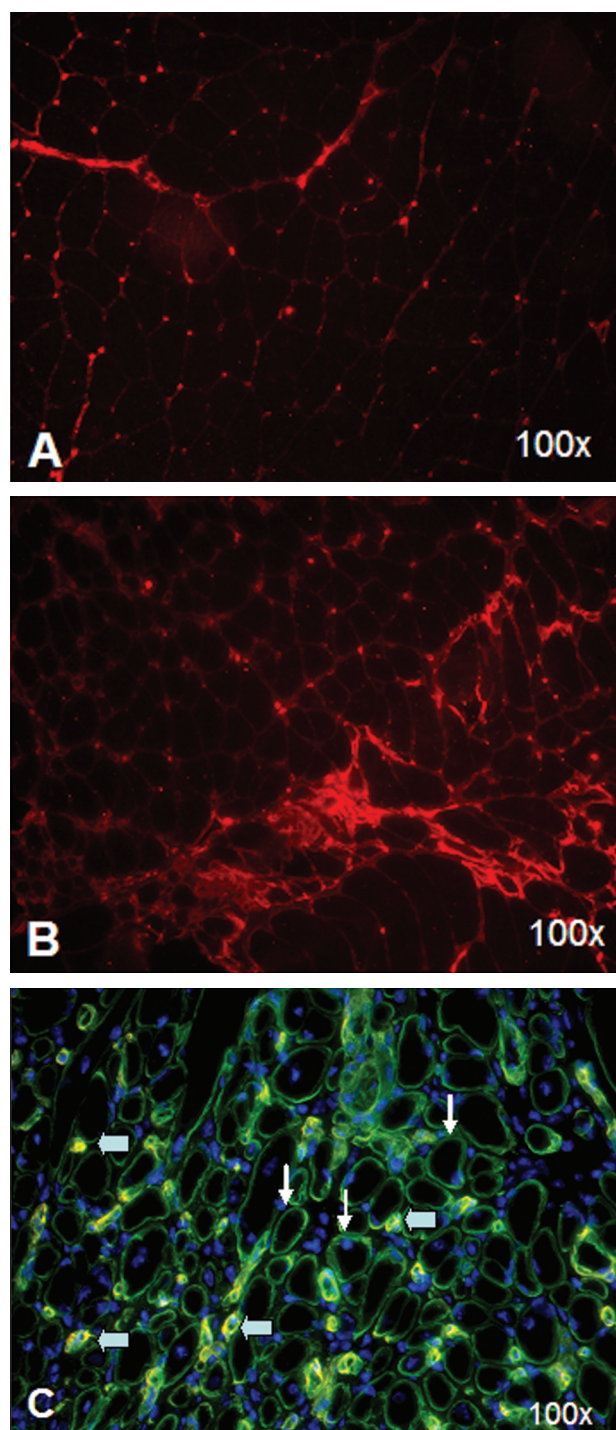
### In Vitro

*Angiotensin II does not affect cell proliferation.* Angiotensin II appeared to have no effect on C2C12 (myoblast cell line), NIH 3T3 (fibroblastic cell line), or PP2 (fibroblast cell line) proliferation in vitro compared with controls at 24, 48, or 72 hours of culture (Table 1).

*Angiotensin II increases the production of TGF $\beta$ -1 in fibroblasts.* Fibroblasts isolated from normal skeletal muscle (PP2 cells) appear to up-regulate the expression of TGF- $\beta$ 1 detected by ELISA in the supernatant fluid when cultured with angiotensin II in a dose-independent manner at both 24 and 48 hours. National Institutes of Health 3T3 fibroblasts also appear to respond to the presence of angiotensin II by expressing TGF- $\beta$ 1, as detected by western blotting (data not shown).

### In Vivo

*Angiotensin II receptors in skeletal muscle.* Immunohistochemistry demonstrated the presence of angiotensin II receptors in both normal and injured skeletal muscle. The



**Figure 1.** Immunohistochemistry demonstrating increased expression of the angiotensin II receptor (red) in injured (B) versus noninjured (A) skeletal muscle. C, the spatial relationships between collagen IV (green), angiotensin II receptor (red), nuclei (blue), and colocalization (yellow) are shown. The angiotensin II receptor distribution (thick arrows) appears more frequently within the extracellular matrix and sarcolemma of muscle fibers than within the myofibers themselves (thin arrows).

distribution of the receptors in normal muscle appeared to be sparse and evenly distributed along the cell membrane. After injury, the expression of angiotensin II receptors appeared elevated, particularly within the zone of injury. The expression of these receptors appeared to be greater within the cellular structure of the extracellular matrix, rather than on the membrane of the muscle fibers (Figure 1).

### Animal Model

All mice used in this experiment were male. No mice demonstrated any ill effects from the treatment regimen, and there were no observable differences in the activity level in any of the groups; no deaths were attributable to the therapeutic intervention. The age of all animals at the beginning of the study ranged from 4 to 6 weeks, and the average weight was  $21.4 \pm 2.3$  g. There was no significant difference in the weight of the animals in the experimental or control groups at any time point. The average dose of ARB received by each animal in the low-dose group and the high-dose group was approximately  $0.027 \pm 0.015$  g/kg/d and  $0.298 \pm 0.20$  g/kg/d, respectively.

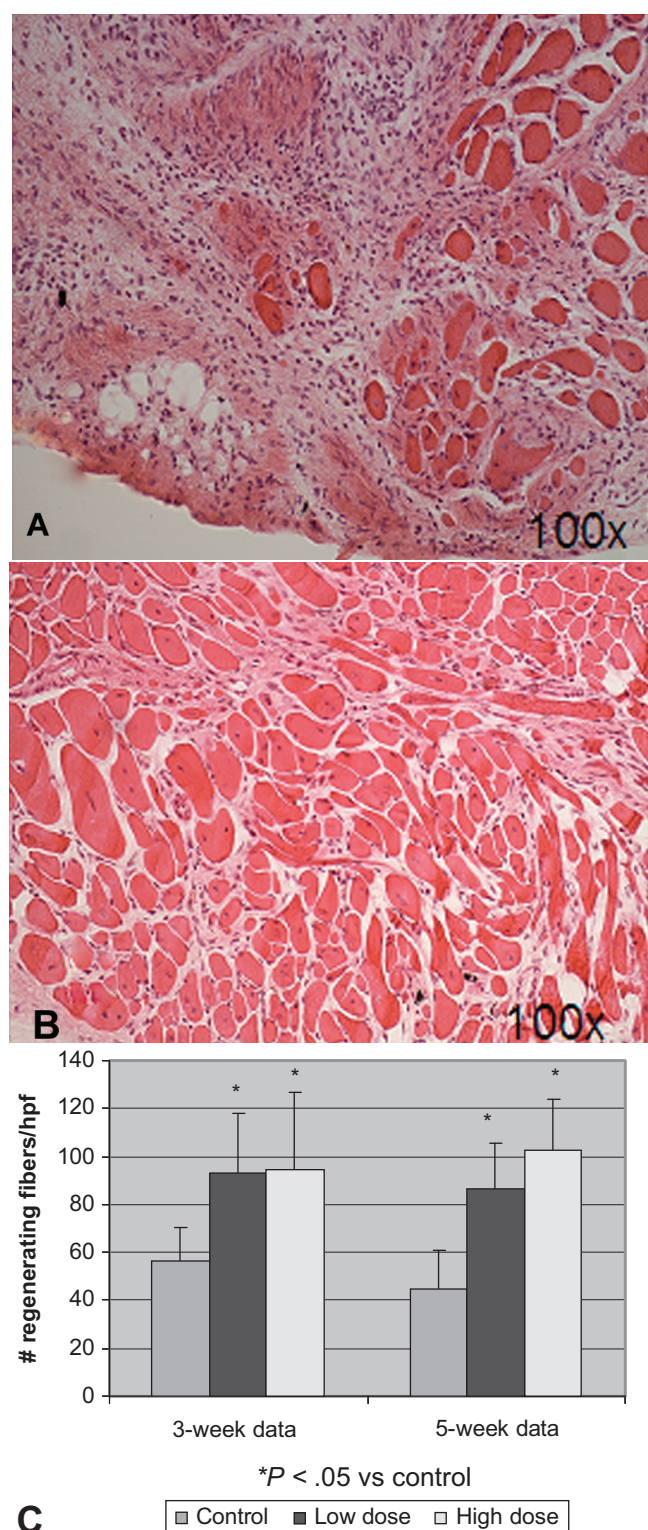
### Skeletal Muscle Regeneration

At 3 weeks, the average number of regenerating myofibers within the zone of injury (as identified by centrally located nuclei) was  $56 \pm 14$  fibers per 200 $\times$  high-powered field ( $n = 4$ ) in the control group,  $93 \pm 25$  ( $n = 8$ ) in the low-dose group, and  $95 \pm 32$  ( $n = 8$ ) in the high-dose group (Figure 2). In injured animals treated for 5 weeks, a statistically significant increase in regenerating myofibers was observed. This increase was  $45 \pm 16$  fibers per 200 $\times$  high-powered field ( $n = 5$ ) in the control group,  $86 \pm 19$  ( $n = 8$ ;  $P < .01$  vs control group) in the low-dose group, and  $103 \pm 21$  ( $n = 7$ ;  $P < .01$  vs control group) in the high-dose group. At both 3 and 5 weeks, the authors observed a trend toward increasingly greater numbers of regenerating myofibers as both the dose and duration of treatment increased (Figure 2).

### Skeletal Muscle Fibrosis

Three weeks after muscle injury, without benefit of treatment, the control group had an area of fibrosis within the zone of injury equal to  $34\% \pm 17\%$  ( $n = 4$ ). The low-dose treatment group had significantly less fibrosis within the zone of injury ( $16\% \pm 9\%$ ;  $n = 8$ ;  $P < .05$ ) when compared with the control group. The high-dose treatment group also had significantly less fibrosis ( $7\% \pm 4\%$ ;  $n = 8$ ;  $P < .01$  vs control) when compared with the control group. At 5 weeks after injury, the control group, low-dose group, and high-dose group had fibrosis areas of  $45\% \pm 22\%$  ( $n = 5$ ),  $19\% \pm 9\%$  ( $n = 8$ ;  $P < .01$  vs control), and  $14\% \pm 11\%$  ( $n = 7$ ;  $P < .01$  vs control), respectively, demonstrating a similar trend toward an attenuation of fibrosis mediated by the administration of losartan (Figure 3).





**Figure 2.** Characteristic hematoxylin-and-eosin-stained sections taken 5 weeks after laceration injury of the gastrocnemius muscle. Note the greater number of regenerating myofibers (recognized by their centrally located nuclei) in the high-dose angiotensin receptor blocker (ARB)-treated group (B) compared with the control group (A). The graph (C) depicts an increase in the number of regenerating myofibers in ARB-treated animals compared with controls. Error bars represent standard deviation. hpf, high-powered field.

## DISCUSSION

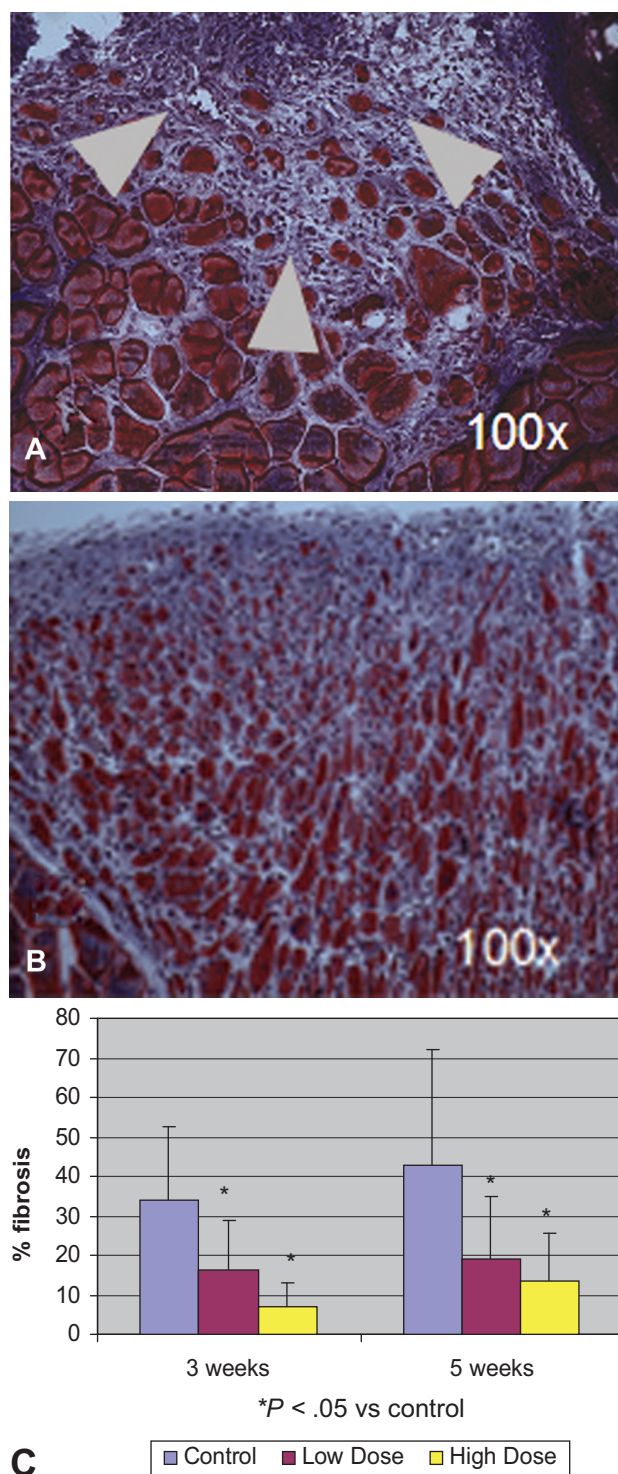
The impetus for investigating the antifibrotic properties of ARBs in muscle healing arises from prior research on angiotensin II, a known vasoconstrictor and target of many antihypertensive medications, demonstrating its deleterious effects on smooth and myocardial muscle tissues after injurious insults. The role of angiotensin II in muscle fibrosis after injury is well documented in the cardiac literature, in which antagonism of angiotensin II with ARBs is noted to significantly improve cardiac contractility and cardiac output.<sup>15</sup> Moreover, histologic analysis indicates that the mechanism of cardiac improvement is related to decreased fibrosis and enhanced regeneration. The effect of ARBs on skeletal muscle healing, however, remains largely unstudied until recently.

The natural history of skeletal muscle injury is that of residual fibrosis within regenerate tissues that predisposes muscle to reinjury and reduced functionality, thereby constituting a significant clinical burden. After injury, the initial phase of myofiber regeneration wanes over time as it is replaced by fibrous tissue. A reduction of fibrous tissue and the improvement of muscle regeneration correlate with enhanced function.

Several investigations have observed this by treating injured skeletal muscle with antifibrotic agents that directly antagonize TGF- $\beta$ 1, and the digestion of existing fibrous tissue deposits appears to enhance myofiber regeneration.<sup>5,9,13,14,23,24</sup> Research on the pathogenesis of fibrosis further reveals that local levels of TGF- $\beta$ 1 during the fibrotic phase are elevated along the zone of injury<sup>21</sup> as a potential result of angiotensin II.<sup>10</sup>

In a mechanism consistent with these studies, we show through ELISA and western blot assays that fibroblasts increase TGF- $\beta$ 1 production when they are exposed to angiotensin II. We also show that angiotensin II receptors are more densely distributed within the extracellular matrix of the zone of injury, suggesting that angiotensin II receptor upregulation is intimately related to the deposition of fibrous tissue. Our results further demonstrate that inhibiting angiotensin II with an ARB diminishes post-traumatic fibrosis.

We have previously focused our attention on muscle injury models such as ischemia, contusion, strain, and cardiotoxin injection. While skeletal muscle laceration is a less frequently observed injury pattern, its histopathology is nearly identical to the more commonly observed strain injury patterns. Our purpose in choosing the laceration model in this experiment was 2-fold. First, it represents a reproducible model for evaluating skeletal muscle injury, which is a challenge with the more common strain-type injury model because of difficulty in accurately reproducing and delivering the same magnitude of injury between samples. Second, the laceration model establishes a "worst-case scenario" in which myofibers are completely transected. Observations of any treatment effect in this worst-case injury model would likely be of equal or, perhaps, greater benefit in less severe and more commonly encountered problems like strain injuries. In addition, the animals were not pretreated with ARB before injury, as this more closely resembles clinically relevant scenarios in which muscle injuries are treated. While many potential



**Figure 3.** Masson's trichrome (collagen: blue, myofibers: red, nuclei: black) staining of sections taken 5 weeks after laceration injury of the gastrocnemius. Note the dense blue staining fibrous tissue in the control group (A) (arrowheads) compared with the high-dose angiotensin receptor blocker (ARB)-treated group (B). Both pictures are taken at 100 $\times$  magnification. The graph (C) depicts a decrease in the amount of fibrosis in ARB-treated animals compared with controls. Error bars represent standard deviation.

problems exist with the use of an antihypertensive medication, all doses administered to the animals in this study were below the corresponding human dose equivalent for the antihypertensive effect of losartan. Accordingly, there were no ill effects observed in any of the animals.

Treating skeletal muscle-injured mice with an ARB for extended periods of time reduces the amount of fibrosis and enhances the number of regenerating myofibers in the zone of injury. This occurs in a duration-dependent manner, where medication administered for longer periods of time provided greater regenerative benefit. The observation of a positive regenerative effect after only 5 weeks of treatment, as opposed to other models where treatment was given for up to 9 months, is of notable significance. Prolonged treatment for acute skeletal muscle injuries would seem to be a less attractive and less pragmatic approach.

Similar success in reducing residual fibrosis and enhancing myofiber regeneration, as well as success in improving function, has been observed in animal models, albeit after treatment with potentially harmful compounds. As noted above, we have demonstrated that decorin, suramin, gamma-interferon, and relaxin can all decrease residual fibrosis, enhance myofiber regeneration, and improve function in animal models of skeletal injury.<sup>9,13,14,22,24</sup> However, these compounds are not commonly employed in clinical practice, and several of these are known to have relatively severe side effects that may preclude their use in the treatment of muscle injury.

While the clinical implications of identifying efficacious antifibrotic therapies are particularly important in the field of sports medicine, they apply to an even broader spectrum of orthopaedic patients. Athletes with muscle strains often struggle with lengthy recovery periods in rehabilitation that can limit their duration of play and predispose them to recurrent injuries that oftentimes are more severe.<sup>26</sup> For orthopaedic trauma patients, contusions and lacerations are markedly common, and for all patients undergoing elective and emergent procedures, many surgical incisions are essentially controlled lacerations of skeletal muscle. In each type of patient, the quality of regenerate skeletal muscle and the rate of recovery are, ultimately, compromised and delayed by fibrosis. For some patients, this can result in prolonged immobilization with greater risks for developing a deep venous thrombus or pneumonia. Because the clinical use of angiotensin receptor II inhibitors is not currently approved for orthopaedic surgery, clinical trials are necessary to further determine the effect of this class of medication on skeletal muscle healing, as well as on the functional outcomes, morbidity, and mortality associated with skeletal muscle injury and prolonged rehabilitation.

In light of the possibility that our work may pave the way for clinical trials on the effect of losartan as an antifibrotic therapy to promote optimal skeletal muscle healing, it is important to draw attention to potential adverse effects of angiotensin II receptor antagonists. The side effect profile of ARBs is surprisingly minimal compared with other antihypertensive medications; the only reported dose-related side effect is hypotension, while non-dose-related adverse outcomes include headaches, dizziness,



weakness, and fatigue.<sup>3</sup> This is particularly worth mentioning because these side effects can theoretically affect athletic performance on the field as well as patient performance in a rehabilitation program. Accordingly, clinicians and therapists must be vigilant in monitoring for such effects. While uncommon, there have also been reports of raised liver enzymes, cholestatic hepatitis, and pancreatitis with losartan.<sup>7,8,23</sup> Finally, while ARBs are more well known for their renoprotective effects, any diuretic generally carries the potential for acute renal insufficiency, which can be a particular concern that especially warrants mentioning in settings where patients may be dehydrated from athletic exertion or blood losses in postoperative and trauma settings.

In summary, the use of the ARB losartan, a commercially available, generally well-tolerated, safe, and widely used antihypertensive medication, has been demonstrated in this study to enhance muscle healing by reducing fibrosis and enhancing muscle regeneration in doses below those required for any antihypertensive effect. These findings may represent the most clinically appealing and potentially far-reaching antifibrotic therapy developed so far for otherwise healthy individuals who have sustained acute skeletal muscle injuries.

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## REFERENCES

- Almekinders LC. Anti-inflammatory treatment of muscular injuries in sports. *Sports Med*. 1993;15(3):139-145.
- American Academy of Family Physicians. *ICD-9 Codes for Family Medicine 2005-2006*. 2005.
- Aronson, Jeffrey K. Angiotensin II receptor antagonists. In: JK Aronson, ed. *Meyler's Side Effects of Drugs: The International Encyclopedia of Adverse Drug Reactions and Interactions*. Amsterdam: Elsevier; 2006:223-226.
- Bedair H, Li Y, Huard J. Angiotensin receptor blockers improve muscle regeneration and decrease fibrosis in injured skeletal muscle. *Trans Orthop Res Soc*. 2005;30:524.
- Bedair H, Liu T, Kaar J, et al. Matrix metalloproteinase-1 therapy improves muscle healing. *J Appl Physiol*. 2007;102:2338-2345.
- Best TM, Shehadeh SE, Levenson G, Michel JT, Corr DT, Aeschlimann D. Analysis of changes in mRNA levels of myoblast- and fibroblast-derived gene products in healing skeletal muscle using quantitative reverse transcription-polymerase chain reaction. *J Orthop Res*. 2001;19(4):565-572.
- Bosch X. Losartan-induced acute pancreatitis. *Ann Intern Med*. 1997;127:1043-1044.
- Bosch X. Losartan-induced hepatotoxicity. *JAMA*. 1997;278:1572.
- Chan YS, Li Y, Foster W, et al. Antifibrotic effects of suramin in injured skeletal muscle after laceration. *J Appl Physiol*. 2003;95(2):771-780.
- Cohn RD, van Erp C, Habashi JP, et al. Angiotensin II type 1 receptor blockade attenuates TGF- $\beta$ -induced failure of muscle regeneration in multiple myopathic states. *Nat Med*. 2007;13(2):204-210.
- Cozaar [package insert]. West Point, PA: Merck & Co Inc; 1995.
- Folland J, Leach B, Little T, et al. Angiotensin-converting enzyme genotype affects the response of human skeletal muscle to functional overload. *Exp Physiol*. 2000;85(5):575-579.
- Foster W, Li Y, Usas A, Somogyi G, Huard J. Gamma interferon as an antifibrosis agent in skeletal muscle. *J Orthop Res*. 2003;21(5):798-804.
- Fukushima K, Badlani N, Usas A, Riano F, Fu F, Huard J. The use of an antifibrosis agent to improve muscle recovery after laceration. *Am J Sports Med*. 2001;29(4):394-402.
- Gremmler B, Kunert M, Schleiting H, Ulbricht JL. Improvement of cardiac output in patients with severe heart failure by use of ACE-inhibitors combined with the AT1-antagonist eprosartan. *Eur J Heart Fail*. 2000;2(2):183-187.
- Huard J, Li Y, Fu FH. Muscle injuries and repair: current trends in research. *J Bone Joint Surg Am*. 2002;84(5):822-832.
- Hurme T, Kalimo H, Lehto M, Jarvinen M. Healing of skeletal muscle injury: an ultrastructural and immunohistochemical study. *Med Sci Sports Exerc*. 1991;23(7):801-810.
- Jarvinen MJ, Lehto MU. The effects of early mobilization and immobilization on the healing process following muscle injuries. *Sports Med*. 1993;15(2):78-89.
- Kalimo H, Rantanen J, Jarvinen M. Muscle injuries in sports. *Baillieres Clin Orthop*. 1997;2:1-24.
- Kherif S, Lafuma C, Dehaupas M, et al. Expression of matrix metalloproteinases 2 and 9 in regenerating skeletal muscle: a study in experimentally injured and mdx muscles. *Dev Biol*. 1999;205(1):158-170.
- Li Y, Huard J. Differentiation of muscle-derived cells into myofibroblasts in injured skeletal muscle. *Am J Pathol*. 2002;161(3):895-907.
- Li Y, Negishi S, Sakamoto M, Usas A, Huard J. The use of relaxin improves healing in injured muscle. *Ann N Y Acad Sci*. 2005;1041:395-397.
- Lim DS, Lutucuta S, Bachireddy P, et al. Angiotensin II blockade reverses myocardial fibrosis in a transgenic mouse model of human hypertrophic cardiomyopathy. *Circulation*. 2001;103(6):789-791.
- Negishi S, Li Y, Usas A, Fu FH, Huard J. The effect of relaxin treatment on skeletal muscle injuries. *Am J Sports Med*. 2005;33(12):1816-1824.
- Onder G, Vedova CD, Pahor M. Effects of ACE inhibitors on skeletal muscle. *Curr Pharm Des*. 2006;12(16):2057-2064.
- Orchard J, Best T. The management of muscle strain injuries: an early return versus the risk of recurrence. *Clin J Sport Med*. 2002;12(1):3-5.
- Otsuka M, Takahashi H, Shiratori M, Chiba H, Abe S. Reduction of bleomycin-induced lung fibrosis by candesartan cilexetil, an angiotensin II type 1 receptor antagonist. *Thorax*. 2004;59(1):31-38.
- Paizis G, Gilbert RE, Cooper ME, et al. Effect of angiotensin II type 1 receptor blockade on experimental hepatic fibrogenesis. *J Hepatol*. 2001;35(3):376-385.
- Qu-Petersen Z, Deasy B, Jankowski R, et al. Identification of a novel population of muscle stem cells in mice: potential for muscle regeneration. *J Cell Biol*. 2002;157(5):851-864.
- Suga S, Mazzali M, Ray PE, Kang DH, Johnson RJ. Angiotensin II type 1 receptor blockade ameliorates tubulointerstitial injury induced by chronic potassium deficiency. *Kidney Int*. 2002;61(3):951-958.
- Swedberg K, Kjeksus J. Effects of enalapril on mortality in severe congestive heart failure: results of the Cooperative North Scandinavian Enalapril Survival Study (CONSENSUS). *Am J Cardiol*. 1988;62(2):60A-66A.
- Woods C, Hawkins RD, Maltby S, et al. The Football Association Medical Research Programme: an audit of injuries in professional football—analysis of hamstring injuries. *Br J Sports Med*. 2004;38(1):36-41.
- Worrell TW. Factors associated with hamstring injuries. An approach to treatment and preventative measures. *Sports Med*. 1994;17(5):338-345.



# Interaction Between Macrophages, TGF- $\beta$ 1, and the COX-2 Pathway During the Inflammatory Phase of Skeletal Muscle Healing After Injury

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Inflammation, an important phase of skeletal muscle healing, largely involves macrophages, TGF- $\beta$ 1, and the COX-2 pathway. To improve our understanding of how these molecules interact during all phases of muscle healing, we examined their roles in muscle cells *in vitro* and *in vivo*. Initially, we found that depletion of macrophages in muscle tissue led to reduced muscle regeneration. Macrophages may influence healing by inducing the production of TGF- $\beta$ 1 and PGE<sub>2</sub> in different muscle cell types. We then found that the addition of TGF- $\beta$ 1 induced PGE<sub>2</sub> production in muscle cells, an effect probably mediated by COX-2 enzyme. It was also found that TGF- $\beta$ 1 enhanced macrophage infiltration in wild-type mice after muscle injury. However, this effect was not observed in COX-2<sup>-/-</sup> mice, suggesting that the effect of TGF- $\beta$ 1 on macrophage infiltration is mediated by the COX-2 pathway. Furthermore, we found that PGE<sub>2</sub> can inhibit the expression of TGF- $\beta$ 1. PGE<sub>2</sub> and TGF- $\beta$ 1 may be involved in a negative feedback loop balancing the level of fibrosis formation during skeletal muscle healing. In conclusion, our results suggest a complex regulatory mechanism of skeletal muscle healing. Macrophages, TGF- $\beta$ 1, and the COX-2 pathway products may regulate one another's levels and have profound influence on the whole muscle healing process. *J. Cell. Physiol.* 214: 405–412, 2008. © 2007 Wiley-Liss, Inc.

Tissue naturally responds to injury caused by trauma, microorganisms, toxins, or other causes through inflammation. Cytokines including histamine, bradykinin, serotonin, prostaglandins and others are released by damaged tissue and cause fluid leakage from blood vessels. These cytokines also attract white blood cells to infiltrate and migrate to the injury site to digest pathogens and dead/damaged cells, a process called phagocytosis. White blood cells and cytokines are of paramount importance for protection against infection and the invasion of foreign substances. Furthermore, they are involved with the regeneration of damaged tissues (Prisk and Huard, 2003; Tidball, 2005).

Skeletal muscle injury is a common type of injury associated with sports activities, high speed vehicle accidents, and military combat. In injured skeletal muscle, the inflammation response starts rapidly after trauma, and causes symptoms that include muscle pain, swelling, fever, and loss of mobility. To relieve these symptoms, many different non-steroidal anti-inflammatory drugs (NSAIDs) are used to block the cyclooxygenase (COX) enzymes and the products of the COX pathway, the prostaglandins. Early studies reported that NSAIDs had a favorable effect in quickly reducing muscle weakness and functional loss in the short term following muscle injury (Hasson et al., 1993; Obremsky et al., 1994; Mishra et al., 1995; Dudley et al., 1997). However, some studies reported either no effect or a detrimental effect on long term muscle strength recovery after prolonged NSAIDs treatment (Mishra et al., 1995; Almekinders, 1999). Recently, studies using COX-2 specific inhibitors also showed that the COX-2 pathway, which is mostly induced in pathological situations, is important in promoting muscle regeneration and reducing fibrosis formation (Bondesen et al., 2004; Shen et al., 2005).

Furthermore, it is suggested that the prostaglandins, although the cause of uncomfortable symptoms, are actually beneficial in promoting skeletal muscle healing (Horsley and Pavlath, 2003; Pavlath and Horsley, 2003; Prisk and Huard, 2003).

Interestingly, it has been suggested that two other components of inflammation, macrophages and transforming growth factor-beta1 (TGF- $\beta$ 1), are related to the COX-2 pathway. Macrophages are an important source of COX-2 enzymes and prostaglandins during the inflammation phase

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(Graf et al., 1999; Lee et al., 2002). And, by some reports, the inhibition of the COX-2 pathway reduced the infiltration of macrophages to the injury site (Bondesen et al., 2004; Shen et al., 2005). TGF- $\beta$ 1, well known for its fibrotic effect, was also shown to be important in the inflammation phase as a result of its connection to the COX-2 pathway. TGF- $\beta$ 1 may increase the production of prostaglandin E<sub>2</sub> (PGE<sub>2</sub>) through COX-2, and PGE<sub>2</sub> may inhibit fibroblast proliferation and collagen production to balance the fibrotic effect of TGF- $\beta$ 1 (Goldstein and Polgar, 1982; McAnulty et al., 1997; Keerthisingam et al., 2001). Furthermore, macrophages and TGF- $\beta$ 1 may also be connected to one another, as several studies have shown that macrophages may be an important source of TGF- $\beta$ 1 (Khalil et al., 1989, 1993; Wolff et al., 2004). However, little evidence of these interactions has been demonstrated in muscle cells during skeletal muscle injury.

To further the understanding of the healing mechanism of skeletal muscle injury and the role of inflammation in the muscle healing process, we examined the relationship between the COX-2 pathway, macrophages, and TGF- $\beta$ 1 in skeletal muscle inflammation. We found that these important components form a complex network wherein they appear to regulate each other. These interactions may not only modulate muscle inflammation, but also influence the regeneration and fibrosis phases of skeletal muscle healing.

## Materials and Methods

### Cell isolation and culturing

Myogenic precursor cells (MPCs) were isolated via a previously described preplate technique (Rando and Blau, 1994; Qu et al., 1998). Briefly, gastrocnemius muscles (GMs) were removed from 4-week-old C57BL/6J mice (Jackson Laboratories, Bar Harbor, ME), and minced with scissors. The minced tissues were enzymatically digested by sequential exposure to collagenase, dispase, and trypsin. The muscle cell extracts were then plated on collagen-coated flasks, and different populations were isolated by re-plating the extracts after different time intervals. The late plated population is usually composed of MPCs that have high myogenic potential when induced by low serum culture medium (Qu et al., 1998). Exudate macrophages were isolated according to the technique described before (Robertson et al., 1993). Briefly, mice were injected intraperitoneally with 30 ml thioglycollate broth (BD Biosciences, San Jose, CA). Three days later, the peritoneal macrophages were harvested by centrifugation. Macrophages and MPCs were used for in vitro experiments along with two other cell lines, NIH 3T3 fibroblasts and C2C12 myoblasts. These three types of cells were maintained in proliferation medium (Dulbecco's modified Eagle's medium (DMEM) supplemented with 10% fetal bovine serum (FBS), 10% horse serum (HS), and 0.5% chicken embryo extract).

### ELISA assay

A low serum-containing medium (DMEM supplemented with 1% FBS and 1% HS) was used to culture cells in the experiments of growth factor and cytokine expression. The media from the TGF- $\beta$ 1 (5 ng/ml, Sigma, St. Louis, MO) and PGE<sub>2</sub> (0, 100, 1,000, or 10,000 ng/ml) treatments experiment were collected and kept at  $-80^{\circ}\text{C}$  pending enzyme-linked immunosorbent assay (ELISA). The assay was performed as suggested by the manufacturer's protocols (DE0100 PGE<sub>2</sub> ELISA kit, DE1150 PGF<sub>2 $\alpha$</sub>  ELISA kit, R & D Systems, Inc., Minneapolis, MN).

### Animal model

The Animal Research and Care Committee at the authors' institution approved all experimental protocols for this study (Protocol 29/04). Twenty-four C57BL/6J mice (males, 6 weeks of age, Jackson Laboratories), 4 COX-2 knock-out mice (males,

6 weeks of age, Taconic farm), and their wild-type controls (males, 6 weeks of age, Taconic farm) were used for in vivo experiments. The GMs of the mice were injected with cardiotoxin (CTX, c3987, Sigma), a snake venom, to create a muscle injury. Briefly, the mice were anesthetized by intraperitoneal injection of 0.03 ml ketamine (100 mg/ml) and 0.02 ml xylazine (20 mg/ml). Ten microliters of diluted CTX (or 9  $\mu$ l CTX + 1  $\mu$ l TGF- $\beta$ 1) was injected in the middle mass of each GM. The mice were sacrificed at different time points after injection (1, 3, 5, or 14 days). The GMs were harvested from both legs for either flow cytometry or histological analysis. For the latter purpose, the GMs were fresh-frozen in 2-methylbutane pre-cooled by liquid nitrogen, and stored at  $-80^{\circ}\text{C}$  pending cryosection.

### Macrophage depletion

Clodronate liposomes, were prepared as described previously (Seiler et al., 1997; Tyner et al., 2005). The liposomes act as carriers for clodronate, which is toxic to phagocytic cells. Two days before muscle injury, 1 mg of clodronate liposomes (20 mg/ml) was injected intraperitoneally into C57BL/6J mice to deplete macrophages. Mice injected with empty liposomes were used as controls. Flow cytometry using macrophage marker antibodies (F4/80 and CD-11b) was used to verify the extent of macrophage depletion.

### Hematoxylin and eosin (H & E) staining

The cryosections were fixed in 1% glutaraldehyde for 1 min, and then immersed in hematoxylin for 30 sec. After washing with alcohol acid and ammonia water, they were immersed in eosin for 15 sec. After each step, sections were rinsed with distilled water. The sections were then dehydrated by treatment with alcohols of increasing concentrations (70%, 80%, 95%, and 100%). Following this, the sections were treated with xylene and covered with glass slips. Slides were analyzed on a bright field microscope (NIKON Eclipse E800, Nikon, Tokyo, Japan). Northern Eclipse software (Empix Imaging, Cheektowaga, NY) was used to measure the minor axis diameters of centronucleated regenerating myofibers (i.e., the smallest diameter of a myofiber across the central nucleus; 200 $\times$  magnification; 200 random myofibers obtained from four samples/group).

### Western blot

After washing with PBS, Laemmli sample buffer (BioRad, 161-0737, Hercules, CA) was applied to the surface of culture dishes to collect proteins from live cells. For muscle tissue samples, serial cryosections of 10  $\mu$ m thickness were collected in Eppendorf tubes and treated with T-PER tissue protein extraction agent (78510, Pierce, Rockford, IL) and mixed with Laemmli sample buffer (BioRad, 161-0737). Protein samples were boiled for 5 min, separated on 10% SDS-polyacrylamide electrophoresis gels, and transferred to nitrocellulose membranes. Mouse anti-COX-2 (160112, Cayman, Ann Arbor, MI) and anti-TGF- $\beta$ 1 antibodies (555052, BD Biosciences Pharmingen, San Diego, CA) were applied as primary antibodies, and mouse anti- $\beta$ -actin (Sigma; 1:8,000) was used for protein quantification. The horseradish peroxidase-conjugated secondary antibodies (Pierce) were diluted to 1:5,000 (v/v). Blots were developed by using SuperSignal West Pico Chemiluminescent substrate (Pierce), and positive bands were visualized on X-ray film. All results were analyzed by Northern Eclipse software (Empix Imaging).

### Flow cytometry

The GMs from non-TGF- $\beta$ 1-treated (10  $\mu$ l cardiotoxin injection) and TGF- $\beta$ 1-treated groups (9  $\mu$ l cardiotoxin plus 1  $\mu$ l of 5 ng/ml TGF- $\beta$ 1 injection) were surgically removed before injury, and at 1, 2, 3, and 5 days after injury for serial evaluation. Collagenase, dispase, and trypsin were used to digest the tissue matrix and

isolate the cells. Debris was removed via filtration with 70  $\mu$ m filters.

Cells were treated with 10% mouse serum (Sigma) to block non-specific binding sites. Primary rat anti-CD-11b (conjugated with FITC, R & D Systems, Inc.) and rat anti-F4/80 (conjugated with APC, BD Biosciences, San Jose, CA) antibodies were used in combination to identify neutrophil and macrophage populations. We added 7-amino-actinomycin D (7-AAD; BD Biosciences Pharmingen, San Diego, CA) to exclude non-viable cells from the analysis. Samples were then analyzed via fluorescence activated cell sorting (FACS) Caliber flow cytometer (BD Biosciences) and CellQuest software (BD Biosciences).

### Statistics

A Chi-squared analysis was used to analyze the percent differences between the number of macrophages identified by flow cytometry and western blotting results. Comparisons between two groups were made by the use of an unpaired Student's *t*-test. All other data were analyzed by one-way ANOVA statistical analysis. Post-hoc multiple comparison tests were performed to determine which means differed. A value of  $P < 0.05$  was considered statistically significant. Error bars on figures represent the standard deviation.

## Results

### Macrophage depletion and muscle regeneration

Liposome clodronate was injected intraperitoneally 2 days prior to muscle injury to deplete the macrophage populations in mice. We used flow cytometry to quantify the number of infiltrating macrophages after injury. This macrophage infiltration peaked 2 days post-injury, and decreased quickly after 5 days. Liposome clodronate injection significantly reduced the number of infiltrating macrophages after muscle injury at all time points observed when compared to the empty liposome control group. At 1d, 2d, 3d, and 5d post-injury, liposome clodronate injection decreased macrophage infiltration by 73.2%, 80.2%, 77.4%, and 64.2%, respectively ( $P < 0.05$ , Fig. 1A). As shown on the flow cytometry graph, the macrophage population, which is shown in the S2 quadrant in the empty liposome control mice, was significantly reduced in the clodronate liposome-injected mice (Fig. 1B).

Clodronate liposome-treated mice exhibited reduced muscle regeneration at both 14 and 28 days after injury. The size of regenerating myofibers in liposome clodronate-treated mice was significantly smaller than those observed in the empty liposome control group ( $P < 0.05$ , Fig. 1C–E). However, at 7 days post-injury, there was no significant difference between these two groups.

### Macrophages depletion decreases the expression of TGF- $\beta$ 1

Injured GMs were isolated from empty liposome control and clodronate liposome-injected mice. We examined the TGF- $\beta$ 1 expression level in injured muscle tissue by using Western blot analysis. Our results indicated that, compared to the empty liposome control group, TGF- $\beta$ 1 expression was significantly decreased 3 and 5 days after injury in the clodronate liposome-injected group, which had its macrophages depleted before the creation of muscle injury ( $P < 0.05$ , Fig. 2A,B). These results suggest that macrophages play an important role in inducing the expression of TGF- $\beta$ 1 during the inflammatory phase of skeletal muscle after injury.

### TGF- $\beta$ 1 induces the production of COX-2 enzyme and prostaglandins

To examine the effect of TGF- $\beta$ 1 on the COX-2 pathway, we cultured MPCs and treated them with TGF- $\beta$ 1. We analyzed the COX-2 enzyme level from MPCs treated with TGF- $\beta$ 1 and

the non-treated control cells for 4 days. Western blot analysis showed that COX-2 production was significantly higher in the MPCs treated by TGF- $\beta$ 1 compared to non-treated control cells ( $P < 0.05$ , Fig. 3A,B). We further tested the expression of PGE<sub>2</sub> from different muscle cells, including MPCs, NIH 3T3 fibroblasts, and C2C12 myoblasts, after they were treated with TGF- $\beta$ 1 for 4 days. We found that TGF- $\beta$ 1 treatment increased the expression of PGE<sub>2</sub> significantly in all cell types, when compared to non-treated control cells ( $P < 0.05$ , Fig. 3C).

To further validate the relationship between TGF- $\beta$ 1 and the COX-2 pathway, we used wild-type MPCs as a model system. In this experiment, NS-398 (a COX-2 specific inhibitor) was added to the cell culture to block the COX-2 enzyme activity. This additional treatment ablated the increased PGE<sub>2</sub> expression that was induced by adding TGF- $\beta$ 1 into the cell culture ( $P < 0.05$ , Fig. 3D). In addition, COX-2<sup>-/-</sup> cells had very low levels of PGE<sub>2</sub> expression, even if TGF- $\beta$ 1 was added. This finding suggests that TGF- $\beta$ 1 regulates the production of COX-2 pathway products, and that the enhanced expression of PGE<sub>2</sub> may be mediated by COX-2.

### TGF- $\beta$ 1 increases the infiltration of macrophages through the COX-2 pathway

To examine the effect of TGF- $\beta$ 1 on macrophage infiltration, we created CTX injury (with or without TGF- $\beta$ 1 treatment) on the GMs of wild-type mice. We found that, after TGF- $\beta$ 1 treatment, the number of infiltrating macrophages was significantly increased compared with the CTX-only group at days 1, 2, and 3 after muscle injury ( $P < 0.05$ , Fig. 4A). The same experiment was conducted on COX-2<sup>-/-</sup> mice. Interestingly, we found that the number of infiltrating macrophages actually decreased with the addition of TGF- $\beta$ 1, instead of being increased 3 days after injury ( $P < 0.05$ , Fig. 4B). This further validates the suggestion that the effect of TGF- $\beta$ 1 on macrophage infiltration is mediated at least in part by the COX-2 pathway products.

### PGE<sub>2</sub> decreased the expression of TGF- $\beta$ 1

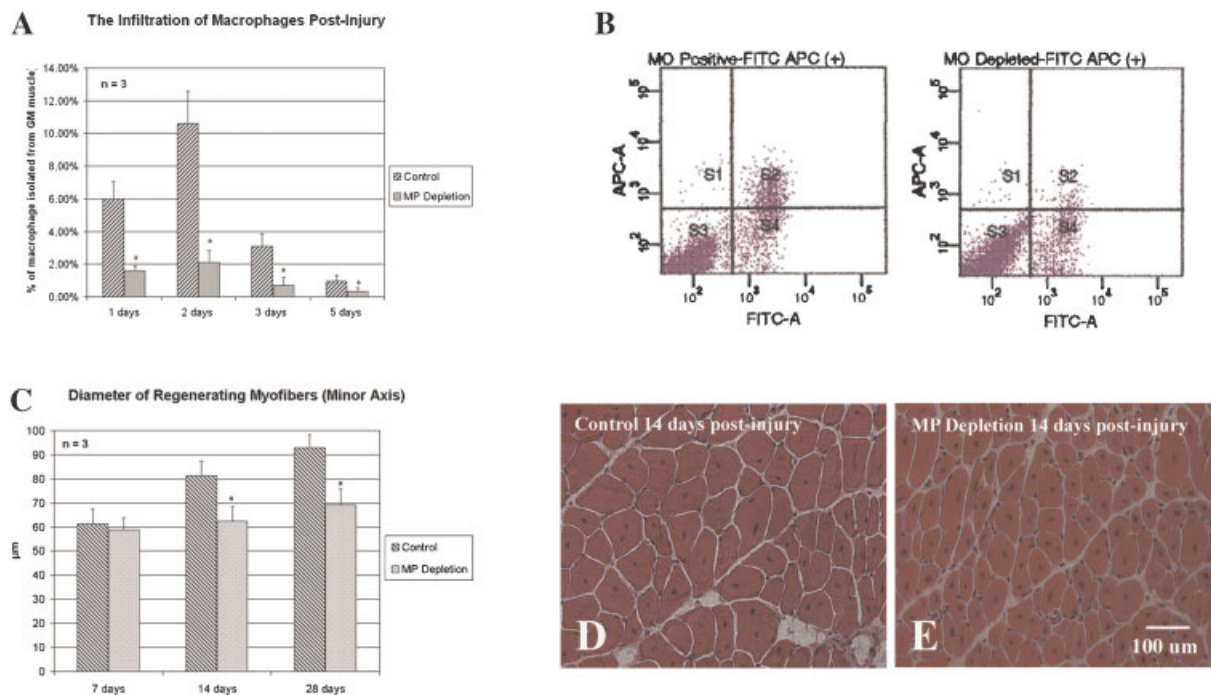
To examine the influence of PGE<sub>2</sub> on fibrosis formation, we chose to examine the effect of PGE<sub>2</sub> treatment on the expression of TGF- $\beta$ 1, which is known for its fibrotic effect especially in skeletal muscle (Li et al., 2004). Three different muscle cell types, MPCs, NIH 3T3 fibroblasts, and C2C12 myoblasts, were tested for TGF- $\beta$ 1 expression following treatment with PGE<sub>2</sub> for 4 days. We found that PGE<sub>2</sub> treatment decreased the expression of TGF- $\beta$ 1 significantly in all cell types tested, when compared to non-treated control cells ( $P < 0.05$ , Fig. 5). This result suggests that PGE<sub>2</sub> may be able to decrease fibrosis formation after muscle injury by decreasing the expression of fibrotic growth factor TGF- $\beta$ 1.

## Discussion

Inflammation is an important phase of skeletal muscle healing. Macrophages, TGF- $\beta$ 1, and the COX-2 pathway are the integral components of this phase. In order to further the understanding of muscle healing and improve the health care of muscle injury patients, we must investigate the importance of these components and elucidate their interaction in muscle healing regulation. In this study, we examined their roles and relationships during the inflammation phase and postulated a possible regulatory mechanism (Fig. 6).

Many researchers suggest that macrophages are important for muscle regeneration (Cantini et al., 2002; Camargo et al., 2003; Chazaud et al., 2003; Tidball, 2005). To create a "Loss of Macrophages Function" condition in skeletal muscle healing, especially in the inflammation phase, we used the clodronate liposome injection technique (Seiler et al., 1997; Tyner et al.,



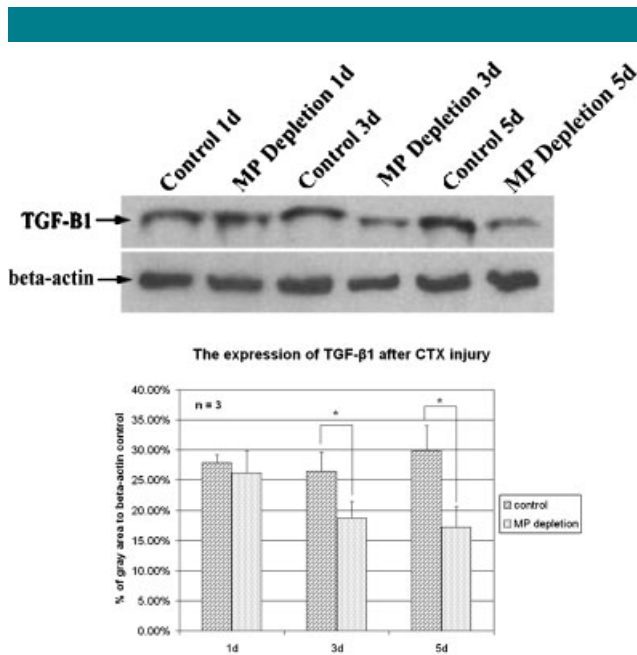


**Fig. 1.** Injection of clodronate liposome depleted macrophages in injured GM significantly after injury. At 1 d, 2 d, 3 d, and 5 d post-injury, liposome clodronate injection decreased macrophage infiltration by 73.2%, 80.2%, 77.4%, and 64.2%, respectively ( $P < 0.05$ , A). Flow cytometry results showed that the macrophage population, which was shown in the S2 quadrant in non-treated mice at 48 h after injury (B, left), was significantly reduced in clodronate liposome-treated mice (B, right). The X-axis represents the CD-11b cell surface marker; and the Y-axis represents the F4/80 cell surface marker. Compared with empty liposome-control group, clodronate liposome-injected mice exhibited significantly reduced sizes of regenerating myofibers 14 and 28 days post-injury ( $P < 0.05$ , C). Sample H & E stained GM sections from empty liposome and clodronate liposome-injected groups 14 days post-injury are shown in (D,E). The asterisks indicate a statistically significant difference ( $P < 0.05$ ) between the marked groups and the control group. The error bars in the graph represent the standard deviation. [Color figure can be viewed in the online issue, which is available at [www.interscience.wiley.com](http://www.interscience.wiley.com).]

2005) to deplete the macrophage populations in mice. With the injection of clodronate liposomes, most of the macrophages were depleted and only a few remaining cells infiltrated into muscle tissue during the inflammation phase. We found that, although regeneration of injured muscle did occur, the macrophage depletion group had significantly smaller myofibers than the non-treated group, which is indicative of a delay in muscle regeneration. This suggests that macrophages participate in the muscle healing process, and may play a beneficial role in the growth of regenerating myofibers.

One of the possible mechanisms by which macrophages contribute to the healing process is by inducing the proliferation and differentiation of satellite cells by secreting growth factors and cytokines (Cantini et al., 1994, 1995; Lescaudron et al., 1999; Merly et al., 1999; Chazaud et al., 2003). The factors secreted by macrophages exert their effects not only on specialized satellite cells during muscle regeneration, but have a broader mitotic activity on all myogenic cells (Cantini and Carraro, 1995). In this study, we found that macrophage-depleted mice had significantly lower TGF- $\beta$ 1 levels in their injured GM muscles compared to those from non-treated control mice. This finding suggests that macrophages play a role in modulating the level of these growth factors including TGF- $\beta$ 1 during the healing process of skeletal muscle. However, the exact role of macrophages and their interaction with other muscle cells warrants further investigation. Studies need to be performed to determine the cellular source of growth factors in the muscle inflammation process, and whether direct contact or humoral regulation is necessary to induce the expression of these growth factors.

Fibrosis is a complex biological process that is usually seen in severe muscle injury. Fibroblasts are activated to proliferate and produce abnormal amounts of extracellular matrix (ECM). Damaged skeletal muscle tissue is replaced by the deposition of overproduced ECM (i.e., fibrosis/scar) tissue, instead of regenerating myofibers. TGF- $\beta$ 1 is one of the most potent fibrotic stimuli (Li et al., 2004). It is an inducer of ECM protein synthesis and fibroblast proliferation (Kahari et al., 1991; Taipale et al., 1994), and it has been implicated in the fibrogenesis of various tissues (Border and Noble, 1994). However, the role of TGF- $\beta$ 1 in skeletal muscle healing is not limited to fibrosis. Previous studies have indicated that TGF- $\beta$ 1 may be an immunosuppressive molecule because its elimination or its downstream Smads signaling cascade disruption leads to severe inflammatory disease (Kulkarni and Karlsson, 1997; Yang et al., 1999; Nakao et al., 2000; Monteleone et al., 2004a). On the other hand, it has been suggested by some authors that TGF- $\beta$ 1 is able to increase PGE<sub>2</sub> expression in other tissues (Fawthrop et al., 1997; McAnulty et al., 1997; Keerthisingam et al., 2001; Han et al., 2004). Since it has been suggested that the COX-2 pathway products including PGE<sub>2</sub> and PGF<sub>2 $\alpha$</sub>  are important inflammatory mediators that induce regeneration in skeletal muscle healing (Bondesen et al., 2004; Shen et al., 2005), it is important to explore their relationship with TGF- $\beta$ 1. In our *in vitro* studies, we found that the addition of TGF- $\beta$ 1 significantly increased the production/expression of both COX-2 enzyme and PGE<sub>2</sub> in muscle cells. By blocking COX-2, TGF- $\beta$ 1's effect on PGE<sub>2</sub> expression was ablated. Furthermore, the effect of TGF- $\beta$ 1 was not observed in COX-2<sup>-/-</sup> cells. These results indicate that TGF- $\beta$ 1 is not only a fibrotic inducer,



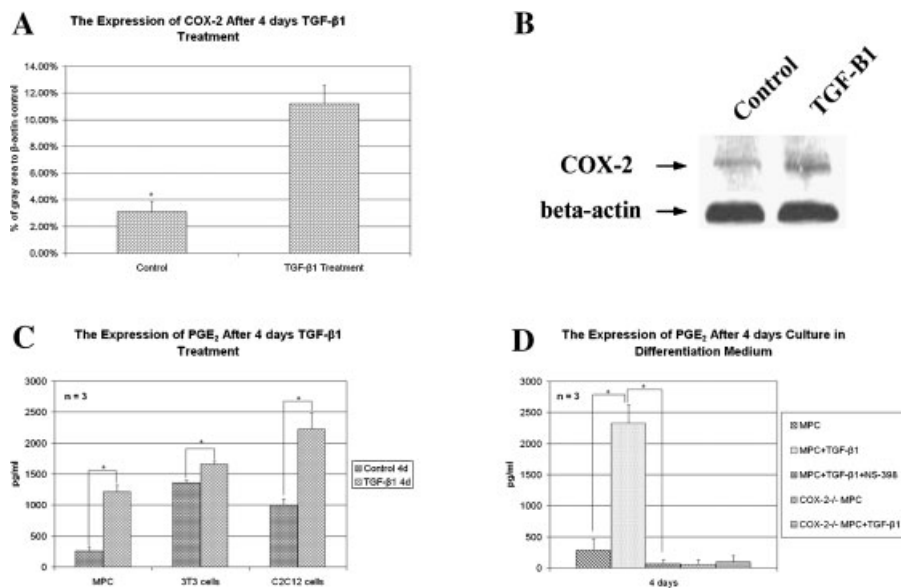
**Fig. 2.** The in vivo expression level of TGF- $\beta$ 1 was significantly lower in the clodronate liposome-injected mice compared to the empty liposome control mice 3 and 5 days after injury ( $P < 0.05$ ). A representative western blot result is shown at the top. The asterisks indicate a significant difference ( $P < 0.05$ ) between the compared groups. The error bars in the graph represent the standard deviation.

but is also an inflammatory modulator in muscle injury. In fact, TGF- $\beta$ 1 may enhance the inflammatory response by enhancing the COX-2 pathway, especially the production of PGE<sub>2</sub>. This may represent an important finding because it indicates that

TGF- $\beta$ 1 may both up- and downregulate inflammation through different pathways.

It has been shown that TGF- $\beta$ 1 interferes with the inflammation phase in various ways (Fiocchi, 2001; Warshamana et al., 2002; Monteleone et al., 2004a,b; Wang et al., 2005). Mostly, TGF- $\beta$ 1 was thought to inhibit inflammation because TGF- $\beta$ 1 is a negative regulator of NF- $\kappa$ B activation (Haller et al., 2003). Smad7 maintains high NF- $\kappa$ B activity during inflammation by blocking TGF- $\beta$ 1 signaling (Monteleone et al., 2004a,b; Wang et al., 2005). To elucidate whether TGF- $\beta$ 1 modulates inflammation by other means, macrophage infiltration for example, we injected TGF- $\beta$ 1 together with CTX. The TGF- $\beta$ 1 addition significantly increased the infiltration of macrophages into injured skeletal muscle. This suggests that TGF- $\beta$ 1 interferes with the inflammation phase of muscle healing by increasing the number of infiltrating macrophages. However, in COX-2<sup>-/-</sup> mice, the number of infiltrating macrophages was decreased with the addition of TGF- $\beta$ 1 to the cardiotoxin injection. This finding suggests that the COX-2 pathway mediates this TGF- $\beta$ 1-induced macrophage infiltration. As prostaglandins are known to cause localized vasodilation, it is reasonable to postulate that they may be at least partly responsible for the chemotaxis of macrophages. In future experiments, prostaglandin's chemotactic property as well as TGF- $\beta$ 1's regulation of NF- $\kappa$ B should be more deeply investigated. If it could be shown that TGF- $\beta$ 1 also has a negative impact on inflammation through the downregulation of NF- $\kappa$ B, it would be intriguing to discover which pathway is dominant in muscle injury, and determine why TGF- $\beta$ 1 would have contradictory effects. Based on the findings that macrophages increased the expression of TGF- $\beta$ 1, and TGF- $\beta$ 1 increased the infiltration of macrophages, which is mediated by the COX-2 pathway, they may form a positive feedback loop to further enhance the number of infiltrating macrophages in the injured muscle (Fig. 6).

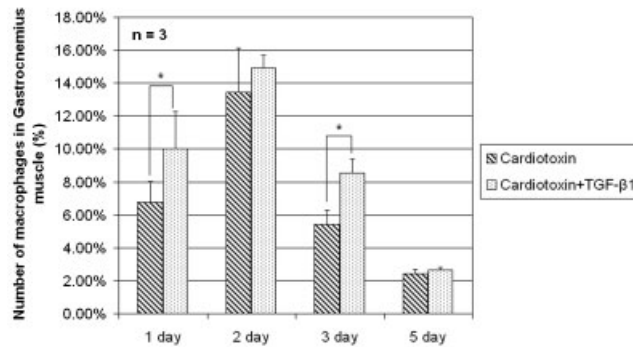
A previous study of liver fibrosis showed that PGE<sub>2</sub> inhibited TGF- $\beta$ 1-mediated induction of collagen alpha 1 production in



**Fig. 3.** MPCs that were treated with TGF- $\beta$ 1 for 4 days had significantly higher production of COX-2 enzyme than the non-treated control cells ( $P < 0.05$ , A). A representative Western blot result is shown in (B). Muscle cells that were treated by TGF- $\beta$ 1 for 4 days had significantly higher expression levels of PGE<sub>2</sub> compared with the non-treated control cells ( $P < 0.05$ , C). NS-398 can significantly reduce the increased PGE<sub>2</sub> expression that was induced by TGF- $\beta$ 1 ( $P < 0.05$ , D). COX-2<sup>-/-</sup> MPC cells, both treated and non-treated with TGF- $\beta$ 1, expressed PGE<sub>2</sub> at very low levels. The asterisks indicate a significant difference ( $P < 0.05$ ) between the compared groups. The error bars in the graph represent the standard deviation.



### A The Effect of TGF- $\beta$ 1 on Macrophage Infiltration After Cardiotoxin-Induced Muscle Injury By Flow Cytometry



### B The Effect of TGF- $\beta$ 1 on Macrophage Infiltration 3 days after CTX Injury in COX-2<sup>-/-</sup> Mice

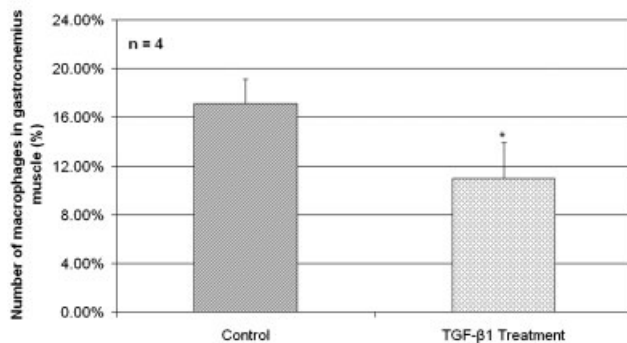


Fig. 4. Flow cytometry results showed that CTX injection can create injury in skeletal muscle and induce the infiltration of macrophages. The addition of TGF- $\beta$ 1 significantly increased the number of infiltrating macrophages at 1 and 3 days after CTX-induced muscle injury ( $P < 0.05$ , A). In contrast, CTX-injured COX-2<sup>-/-</sup> mice showed significantly decreased numbers of infiltrating macrophages 3 days post-injury ( $P < 0.05$ , B). The asterisks indicate a significant difference ( $P < 0.05$ ) between the compared groups. The error bars in the graph represent the standard deviation.

hepatic cells (Hui et al., 2004). This finding suggests that PGE<sub>2</sub> and TGF- $\beta$ 1 are able to regulate one another's levels by forming a negative feedback loop resulting in homeostasis of fibrosis formation. To test this phenomenon in skeletal muscle, we treated different muscle cell types with PGE<sub>2</sub> and analyzed their TGF- $\beta$ 1 expression. What we found was that PGE<sub>2</sub> treatment decreased the expression of TGF- $\beta$ 1 significantly in all muscle cell types, when compared to non-treated control cells. On the other hand, our previous study showed that by using NS-398 to block COX-2, and thus the expression of PGE<sub>2</sub>, the expression of TGF- $\beta$ 1 was increased in injured muscle tissue (Shen et al., 2005). These results indicate that the TGF- $\beta$ 1 level was probably regulated by PGE<sub>2</sub>. The application of NS-398 probably inhibited PGE<sub>2</sub> expression and led to a high level of TGF- $\beta$ 1, and subsequent fibrosis formation in injured muscle. Our findings are consistent with the results from a previous liver fibrosis study (Hui et al., 2004), and further suggests the existence of a negative feedback loop between TGF- $\beta$ 1 and PGE<sub>2</sub> in skeletal muscle (Fig. 6).

PGE<sub>2</sub> is also a potent inhibitor of fibroblast proliferation (Goldstein and Polgar, 1982; Durant et al., 1989) and collagen

### The Expression of TGF- $\beta$ 1 by Muscle Cells after Treated with PGE<sub>2</sub> for 4 days

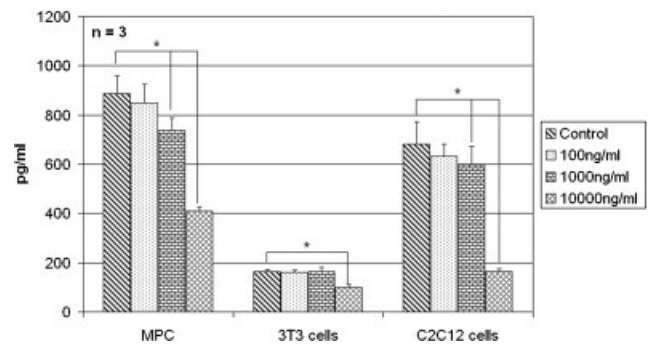


Fig. 5. At concentrations of 1,000 ng/ml and 10,000 ng/ml, PGE<sub>2</sub> decreased the expression of TGF- $\beta$ 1 significantly in both MPCs and C2C12 myoblasts. However, PGE<sub>2</sub> was able to decrease the expression of TGF- $\beta$ 1 in NIH 3T3 fibroblasts only at a concentration of 10,000 ng/ml ( $P < 0.05$ ). The asterisks indicate a significant difference ( $P < 0.05$ ) between the compared groups. The error bars in the graph represent the standard deviation.

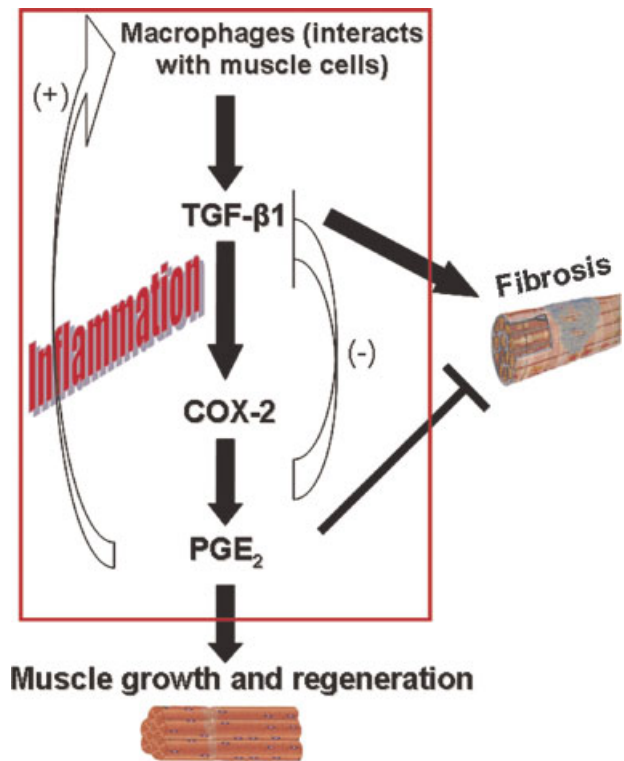


Fig. 6. The proposed mechanism of muscle inflammation is shown. Macrophages interact with muscle cells to increase the level of TGF- $\beta$ 1 in muscle inflammation. TGF- $\beta$ 1 increases the level of prostaglandins, which mediates muscle regeneration and the further infiltration of macrophages, forming a positive feedback loop. In turn, PGE<sub>2</sub> decreases the expression of TGF- $\beta$ 1 and forms a negative feedback loop to downregulate the fibrosis formation. Macrophages, muscle cells, TGF- $\beta$ 1, and COX-2 pathway form a complex network to regulate each other, and thus modulate the following regeneration and fibrosis formation during the healing process after injury. [Color figure can be viewed in the online issue, which is available at [www.interscience.wiley.com](http://www.interscience.wiley.com).]

synthesis (Goldstein and Polgar, 1982; Saltzman et al., 1982). This suggests that PGE<sub>2</sub> may play an important role in minimizing ECM production. This is especially important in an environment favoring fibrosis formation, such as is found within the inflammation of damaged liver. Interestingly, our preliminary data showed that different concentrations of PGE<sub>2</sub> may affect the proliferation of muscle cells differently (data not shown). Thus, the next step in our study would be to assess the level of PGE<sub>2</sub> in injured skeletal muscle, which should give further insight into the effect of PGE<sub>2</sub> on muscle cell proliferation. It is also important to investigate the role of other prostaglandins, such as PGF<sub>2α</sub>, PGE<sub>2</sub>, and 15-PG dehydrogenase in the future, because other prostaglandins may also play a role in the muscle healing process, and 15-PG dehydrogenase may have a significant effect on prostaglandin levels.

In summary, our study demonstrates that the COX-2 pathway, macrophages, and TGF-β1 are important components of the inflammation phase of injured skeletal muscle. Inflammation affects the overall healing of skeletal muscle through these cellular and molecular components. In addition, we found that these components may modulate the production of each other and form a complex co-regulatory mechanism. As we begin to comprehend the fact that simply blocking inflammation by using NSAIDs has a potential downside on muscle healing, more studies are warranted to improve the quality of healthcare in patients afflicted with skeletal muscle injuries.

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## Literature Cited

- Almekinders LC. 1999. Anti-inflammatory treatment of muscular injuries in sport. An update of recent studies. *Sports Med* 28:383–388.
- Bondesen BA, Mills ST, Kegel KM, Pavlath GK. 2004. The COX-2 pathway is essential during early stages of skeletal muscle regeneration. *Am J Physiol Cell Physiol* 287:C475–C483.
- Border WA, Noble NA. 1994. Transforming growth factor beta in tissue fibrosis. *N Engl J Med* 331:1286–1292.
- Camargo FD, Green R, Capetenaki Y, Jackson KA, Goodell MA. 2003. Single hematopoietic stem cells generate skeletal muscle through myeloid intermediates. *Nat Med* 9:1520–1527.
- Cantini M, Carraro U. 1995. Macrophage-released factor stimulates selectively myogenic cells in primary muscle culture. *J Neuropathol Exp Neurol* 54:121–128.
- Cantini M, Massimino ML, Brusson A, Catani C, Dalla Libera L, Carraro U. 1994. Macrophages regulate proliferation and differentiation of satellite cells. *Biochem Biophys Res Commun* 202:1688–1696.
- Cantini M, Massimino ML, Rapizzi E, Rossini K, Catani C, Dalla Libera L, Carraro U. 1995. Human satellite cell proliferation in vitro is regulated by autocrine secretion of IL-6 stimulated by a soluble factor(s) released by activated monocytes. *Biochem Biophys Res Commun* 216:49–53.
- Cantini M, Giuriso E, Radu C, Tiozzo S, Pampinella F, Senigaglia D, Zaniolo G, Mazzoleni F, Vitiello L. 2002. Macrophage-secreted myogenic factors: A promising tool for greatly enhancing the proliferative capacity of myoblasts in vitro and in vivo. *Neurol Sci* 23:189–194.
- Chazaud B, Sonnet C, Lafuste P, Bassez G, Rimaniol AC, Poron F, Authier FJ, Dreyfus PA, Gherardi RK. 2003. Satellite cells attract monocytes and use macrophages as a support to escape apoptosis and enhance muscle growth. *J Cell Biol* 163:1133–1143.
- Dudley GA, Czerkaski J, Meinrod A, Gillis G, Baldwin A, Scarpace M. 1997. Efficacy of naproxen sodium for exercise-induced dysfunction muscle injury and soreness. *Clin J Sport Med* 7:3–10.
- Durant S, Duval D, Homo-Delarche F. 1989. Effect of exogenous prostaglandins and nonsteroidal anti-inflammatory agents on prostaglandin secretion and proliferation of mouse embryo fibroblasts in culture. *Prostaglandins Leukot Essent Fatty Acids* 38:1–8.
- Fawthrop FW, Frazer A, Russell RG, Bunning RA. 1997. Effects of transforming growth factor beta on the production of prostaglandin E and caseinase activity of unstimulated and interleukin 1-stimulated human articular chondrocytes in culture. *Br J Rheumatol* 36:729–734.
- Fiocchi C. 2001. TGF-beta/Smad signaling defects in inflammatory bowel disease: Mechanisms and possible novel therapies for chronic inflammation. *J Clin Invest* 108:523–526.
- Goldstein RH, Polgar P. 1982. The effect and interaction of bradykinin and prostaglandins on protein and collagen production by lung fibroblasts. *J Biol Chem* 257:8630–8633.
- Graf BA, Nazarenko DA, Borrello MA, Roberts LJ, Morrow JD, Palis J, Phipps RP. 1999. Biphentotypic B/macrophage cells express COX-1 and up-regulate COX-2 expression and prostaglandin E(2) production in response to pro-inflammatory signals. *Eur J Immunol* 29:3793–3803.
- Haller D, Holt L, Kim SC, Schwabe RF, Sartor RB, Jobin C. 2003. Transforming growth factor-beta 1 inhibits non-pathogenic Gram negative bacteria-induced NF-kappa B recruitment to the interleukin-6 gene promoter in intestinal epithelial cells through modulation of histone acetylation. *J Biol Chem* 278:23851–23860.
- Han C, Demetris AJ, Liu Y, Shelhamer JH, Wu T. 2004. Transforming growth factor-beta (TGF-beta) activates cytosolic phospholipase A2alpha (cPLA2alpha)-mediated prostaglandin E2 (PGE2)/EP1 and peroxisome proliferator-activated receptor-gamma (PPAR-gamma)/Smad signaling pathways in human liver cancer cells. A novel mechanism for subversion of TGF-beta-induced mitoinhibition. *J Biol Chem* 279:44344–44354.
- Hasson SM, Daniels JC, Divine JG, Niebuhr BR, Richmond S, Stein PG, Williams JH. 1993. Effect of ibuprofen use on muscle soreness, damage, and performance: A preliminary investigation. *Med Sci Sports Exerc* 25:9–17.
- Horsley V, Pavlath GK. 2003. Prostaglandin F2(alpha) stimulates growth of skeletal muscle cells via an NFATC2-dependent pathway. *J Cell Biol* 161:1111–1118.
- Hui AY, Dannenberg AJ, Sung JJ, Subbaramaiah K, Du B, Olinga P, Friedman SL. 2004. Prostaglandin E2 inhibits transforming growth factor beta 1-mediated induction of collagen alpha 1(I) in hepatic stellate cells. *J Hepatol* 41:251–258.
- Kahari VM, Larjava H, Uitto J. 1991. Differential regulation of extracellular matrix proteoglycan (PG) gene expression. Transforming growth factor-beta 1 up-regulates biglycan (PGI), and versican (large fibroblast PG) but down-regulates decorin (PGII) mRNA levels in human fibroblasts in culture. *J Biol Chem* 266:10608–10615.
- Keerthisingam CB, Jenkins RG, Harrison NK, Hernandez-Rodriguez NA, Booth H, Laurent GJ, Hart SL, Foster ML, McNulty RJ. 2001. Cyclooxygenase-2 deficiency results in a loss of the anti-proliferative response to transforming growth factor-beta in human fibrotic lung fibroblasts and promotes bleomycin-induced pulmonary fibrosis in mice. *Am J Pathol* 158:1411–1422.
- Khalil N, Berezney O, Sporn M, Greenberg AH. 1989. Macrophage production of transforming growth factor beta and fibroblast collagen synthesis in chronic pulmonary inflammation. *J Exp Med* 170:727–737.
- Khalil N, Whitman C, Zuo L, Danielpour D, Greenberg A. 1993. Regulation of alveolar macrophage transforming growth factor-beta secretion by corticosteroids in bleomycin-induced pulmonary inflammation in the rat. *J Clin Invest* 92:1812–1818.
- Kulkarni AB, Karlsson S. 1997. Inflammation and TGF beta 1: Lessons from the TGF beta 1 null mouse. *Res Immunol* 148:453–456.
- Lee SK, Hong CH, Huh SK, Kim SS, Oh OJ, Min HY, Park KK, Chung WY, Hwang JK. 2002. Suppressive effect of natural sesquiterpenoids on inducible cyclooxygenase (COX-2) and nitric oxide synthase (iNOS) activity in mouse macrophage cells. *J Environ Pathol Toxicol Oncol* 21:141–148.
- Lescaudron L, Peltekian E, Fontaine-Perus J, Paulin D, Zampieri M, Garcia L, Parrish E. 1999. Blood borne macrophages are essential for the triggering of muscle regeneration following muscle transplant. *Neuromuscul Disord* 9:72–80.
- Li Y, Foster W, Deasy BM, Chan Y, Prisk V, Tang Y, Cummins J, Huard J. 2004. Transforming growth factor-beta1 induces the differentiation of myogenic cells into fibrotic cells in injured skeletal muscle: A key event in muscle fibrogenesis. *Am J Pathol* 164:1007–1019.
- McAnulty RJ, Hernandez-Rodriguez NA, Mutsaers SE, Coker RK, Laurent GJ. 1997. Indomethacin suppresses the anti-proliferative effects of transforming growth factor-beta isoforms on fibroblast cell cultures. *Biochem J* 321:639–643.
- Merly F, Lescaudron L, Rouaud T, Crossin F, Gardahaut MF. 1999. Macrophages enhance muscle satellite cell proliferation and delay their differentiation. *Muscle Nerve* 22:724–732.
- Mishra DK, Friden J, Schmitz MC, Lieber RL. 1995. Anti-inflammatory medication after muscle injury. A treatment resulting in short-term improvement but subsequent loss of muscle function. *J Bone Joint Surg Am* 77:1510–1519.
- Monteleone G, Mann J, Monteleone I, Vavassori P, Bremner R, Fantini M, Del Vecchio Blanco G, Tersigni R, Alessandrini L, Mann D, Pallone F, MacDonald TT. 2004a. A failure of transforming growth factor-beta1 negative regulation maintains sustained NF-kappaB activation in gut inflammation. *J Biol Chem* 279:3925–3932.
- Monteleone G, Pallone F, MacDonald TT. 2004b. Smad7 in TGF-beta-mediated negative regulation of gut inflammation. *Trends Immunol* 25:513–517.
- Nakao A, Miike S, Hatano M, Okumura K, Tokuhisa T, Ra C, Iwamoto I. 2000. Blockade of transforming growth factor beta/Smad signaling in T cells by overexpression of Smad7 enhances antigen-induced airway inflammation and airway reactivity. *J Exp Med* 192:151–158.
- Obremsky WT, Seaber AV, Ribbeck BM, Garrett WE, Jr. 1994. Biomechanical and histologic assessment of a controlled muscle strain injury treated with piroxicam. *Am J Sports Med* 22:558–561.
- Pavlath GK, Horsley V. 2003. Cell fusion in skeletal muscle—Central role of NFATC2 in regulating muscle cell size. *Cell Cycle* 2:420–423.
- Prisk V, Huard J. 2003. Muscle injuries and repair: The role of prostaglandins and inflammation. *Histol Histopathol* 18:1243–1256.
- Qu Z, Balkir L, van Deutekom JC, Robbins PD, Pruchnic R, Huard J. 1998. Development of approaches to improve cell survival in myoblast transfer therapy. *J Cell Biol* 142:1257–1267.
- Rando TA, Blau HM. 1994. Primary mouse myoblast purification, characterization, and transplantation for cell-mediated gene therapy. *J Cell Biol* 125:1275–1287.
- Robertson TA, Maley MA, Grounds MD, Papadimitriou JM. 1993. The role of macrophages in skeletal muscle regeneration with particular reference to chemotaxis. *Exp Cell Res* 207:321–331.
- Saltzman LE, Moss J, Berg RA, Hom B, Crystal RG. 1982. Modulation of collagen production by fibroblasts. Effects of chronic exposure to agonists that increase intracellular cyclic AMP. *Biochem J* 204:25–30.
- Seiler P, Aichele P, Odermatt B, Hengartner H, Zinkernagel RM, Schwendener RA. 1997. Crucial role of marginal zone macrophages and marginal zone metallophilic in

- the clearance of lymphocytic choriomeningitis virus infection. *Eur J Immunol* 27: 2626–2633.
- Shen W, Li Y, Tang Y, Cummins J, Huard J. 2005. NS-398, a Cyclooxygenase-2-Specific Inhibitor, Delays Skeletal Muscle Healing by Decreasing Regeneration and Promoting Fibrosis. *Am J Pathol* 167:1105–1117.
- Taipale J, Miyazono K, Heldin CH, Keski-Oja J. 1994. Latent transforming growth factor-beta 1 associates to fibroblast extracellular matrix via latent TGF-beta binding protein. *J Cell Biol* 124:171–181.
- Tidball JG. 2005. Inflammatory processes in muscle injury and repair. *Am J Physiol Regul Integr Comp Physiol* 288:R345–R353.
- Tyner JW, Uchida O, Kajiwaru N, Kim EY, Patel AC, O'Sullivan MP, Walter MJ, Schwendener RA, Cook DN, Danoff TM, Holtzman MJ. 2005. CCL5-CCR5 interaction provides antiapoptotic signals for macrophage survival during viral infection. *Nat Med* 11:1180–1187.
- Wang W, Huang XR, Li AG, Liu F, Li JH, Truong LD, Wang XJ, Lan HY. 2005. Signaling Mechanism of TGF- $\beta$ 1 in Prevention of Renal Inflammation: Role of Smad7. *J Am Soc Nephrol* 16:1371–1383.
- Warshamana GS, Pociask DA, Fisher KJ, Liu JY, Sime PJ, Brody AR. 2002. Titration of non-replicating adenovirus as a vector for transducing active TGF-beta 1 gene expression causing inflammation and fibrogenesis in the lungs of C57BL/6 mice. *Int J Exp Pathol* 83:183–201.
- Wolff RA, Tomas JJ, Hullett DA, Stark VE, van Rooijen N, Hoch JR. 2004. Macrophage depletion reduces monocyte chemotactic protein-1 and transforming growth factor-beta 1 in healing rat vein grafts. *J Vasc Surg* 39:878–888.
- Yang X, Letterio JJ, Lechleider RJ, Chen L, Hayman R, Gu H, Roberts AB, Deng C. 1999. Targeted disruption of SMAD3 results in impaired mucosal immunity and diminished T cell responsiveness to TGF-beta. *Embo J* 18:1280–1291.



# Blocking Myostatin by AAV2-Delivered Myostatin Propeptide Improves Muscle Cell Transplantation

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## INTRODUCTION

Myostatin (MSTN) is a potent negative regulator of muscle growth [1] and we have found that like TGF- $\beta$ 1, MSTN also contributes to the formation of fibrosis in injured skeletal muscle [2]. Jacques-Tremblay's group has successfully blocked MSTN signaling in *mdx* mice by generating 2 types of transgenic *mdx* mice. The 1st carries a dominant negative form of the MSTN receptor (dnActRIIB) and the 2nd over-expresses follistatin (FSTN), which is an inhibitor of MSTN. Normal myoblasts transplanted into these transgenic *mdx* mice outperformed myoblasts transplanted into nontransgenic *mdx* mice [3, 4]; nevertheless, dnActRIIB and FSTN do not specifically inhibit MSTN but also interfere with other growth factors such as activins. In the current study we utilized an adeno-associated viral vector carrying the MSTN propeptide gene (AAV-MPRO) to specifically inhibit the action of MSTN. MPRO directly binds the MSTN molecule and has been shown in previous studies. We have proved that blocking MSTN with MPRO both increase muscle regeneration and reduce the formation of fibrosis at the site of injury 4 weeks following injury (unpublished data). In the current study we injected AAV-MPRO/GFP into the skeletal muscles of *mdx*/SCID mice 4 weeks prior to muscle progenitor cell transplantation to investigate whether blocking MSTN signaling in host muscle by MPRO can elevate the regeneration capacity of donor muscle cells in dystrophic muscle. The success of cell therapy for treating muscle injuries and diseases has been limited by the poor survival and function of the donor cells after transplantation; therefore, improving the microenvironment in the host dystrophic muscle prior to cell transplantation is an alternative approach to enhance the efficiency of cell transplantation.

## METHODS

**Animal model:** All experiments in this study were approved by the Children's Hospital of Pittsburgh IACUC. AAV2-MPRO ( $1 \times 10^{11}$  v.g.) in 50  $\mu$ l of PBS was injected into the gastrocnemius muscles (GMs) of 3 *mdx*/SCID mice (4 weeks of age); the same amount of AAV-GFP was injected into the GMs of *mdx*/SCID littermates as controls. Four weeks after injection of AAV, 300,000 muscle progenitor cells (MPCs) were injected into each of the GMs of AAV treated *mdx*/SCID mice ( $n = 6$ ), and the mice were sacrificed 2 weeks following the cell transplantation. Masson's Trichrome staining was performed to identify fibrous scar tissue in the mice. Northern Eclipse software (Empix Imaging, Inc.) was used to measure the diameters of regenerating myofibers within the injection site and also measure the areas of fibrous scar tissue. Dystrophin staining was performed and the dystrophin-positive myofibers were then counted to assess the efficiency of cell transplantation in the skeletal muscle of the *mdx*/SCID mice. Student's *t* test was used to determine significance ( $P < 0.05$ ).

**Immunohistochemistry:** Muscles were snap frozen in liquid nitrogen, cryosectioned and the tissue sections were then fixed in 5 % formalin for 5 minutes, followed by 3 washes with PBS. The sections were blocked with 10% donkey serum for 1 hour, and incubated overnight at 4°C in either a goat MPRO antibody (2.5  $\mu$ g/ml, RnD system) or a rabbit dystrophin primary antibody (1:500, Abcam) that was diluted in 5% donkey serum. The following day, the sections were washed with PBS and incubated with the corresponding secondary antibodies, rabbit anti-Goat or donkey anti-rabbit IgG conjugated with Alexa594.

## RESULTS

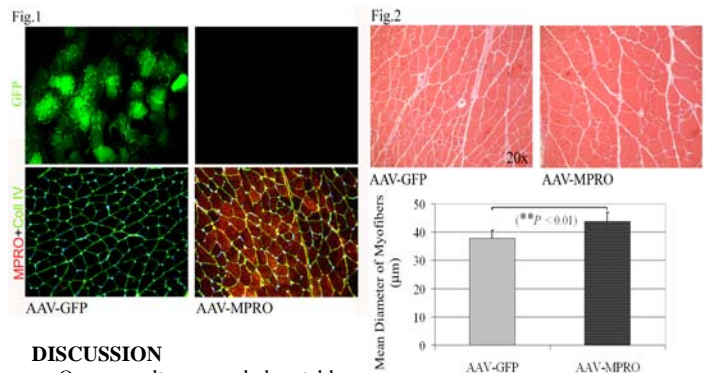
**Gene expression in muscle:** Expressions of GFP (green) and MPRO (red) in AAV-GFP/MPRO transduced muscles indicates that genes delivered by AAV were stably expressed in skeletal muscle (Fig. 1).

**Accelerated muscle regeneration in MPRO over-expressing *mdx*/SCID mice:** Six weeks after AAV2-MPRO transduction, a significant increase in muscle weight was observed compared to the GFP transduced control (data not shown). Moreover, the mean diameter of the muscle fibers in the AAV-MPRO transduced muscles was significantly larger than that of AAV-GFP transduced muscles (Fig. 2).

**Reduced fibrosis:** Masson's trichrome stain showed a reduction of fibrous scar tissue (blue) in the AAV2-MPRO transduced GMs as compared to the AAV-GFP control muscles (Fig. 3).

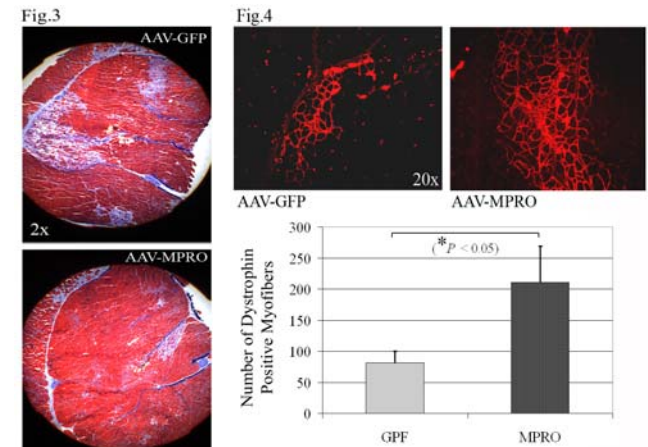
**Improved cell transplantation in the GMs of AAV-MPRO transduced *mdx*/SCID mice:** Fig.4 shows the representative images of dystrophin-positive muscle fibers in the muscles of *mdx*/SCID mice 2 weeks after cell transplantation. Normal MPCs injected into AAV-MPRO transduced dystrophic muscle surpassed the regeneration capacity of cells injected into

AAV-GFP transduced control muscle. This was determined by counting the total number of dystrophin positive myofibers (Fig. 4)



## DISCUSSION

Our results revealed stable expression of AAV-mediated GFP and MPRO in transduced skeletal muscle. MPRO ameliorated the dystrophic pathology of *mdx* mice by promoting muscle regeneration and reducing collagen deposition. Inactivation of MSTN in dystrophic host muscle by MPRO significantly improved the success of MPC transplantation as compared to the AAV-GFP transduced control, evidenced by significantly more dystrophin-positive myofibers in the former. Two mechanisms may account for this improved cell transplantation. First, MPRO counteracts the inhibitory effect that MSTN has on donor cell regeneration. Deregulating the suppression of MSTN on muscle cells by MPRO transduction may augment donor cell proliferation, differentiation, and hence increase dystrophin-positive myofiber formation. Second, the improved cell transplantation in *mdx* mice by MPRO may be partially accredited to the fact that MPRO inhibits MSTN, thereby reducing fibrosis formation in dystrophic muscle. The ameliorated milieu in host dystrophic muscle may favor donor cell survival and engraftment. Taken together, the combination of gene therapy and cell therapy has been shown to be a potential effective and novel approach for treating injured and diseased muscle.



## ACKNOWLEDGMENTS

This work was supported by funding from the Henry J. Mankin Endowed Chair for Orthopaedic Research at the University of Pittsburgh, the William F. and Jean W. Donaldson Chair at Children's Hospital of Pittsburgh, the Hirtzel Foundation, and the National Institutes of Health (R01 AR47973 awarded to J.H.).

## REFERENCES

- McPherron AC et al. Nature 1997;387:83–90.
- Zhu J et al. J Biol Chem 2007; 282(35):25852–63.
- Benabdallah et al. Transplantation 2005; 79(12):1696–702.
- Benabdallah et al. Cell Transplant 2008;17(3):337–50.

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## Angiotensin II Receptor Blocker Ameliorates Skeletal Muscle Healing in a Dose Dependent Manner

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### INTRODUCTION:

Muscle injuries are very common musculoskeletal problems encountered in sports medicine. Although these injuries are capable of healing, complete functional recovery is hindered by the formation of dense scar tissue triggered by TGF- $\beta$ 1 [1]. We have previously reported that several agents such as decorin and suramin can inhibit fibrosis and improve regeneration in injured skeletal muscle. The safety of these agents, however, remains unknowns to use those agents for treating muscle injury. By contrast, Losartan (LOS), one of the Angiotensin II Receptor Blockers (ARBs)—is a FDA approved antihypertensive medication and has been shown to also be antifibrotic in a variety of tissues, including skeletal muscle [2]. This ARB has a well-tolerated side-effect profile, can also block TGF- $\beta$ 1 to attenuate the development of pathological fibrosis. In this study, we investigated optimum dose of LOS in treating injured muscle to help the translation of this research from bench to bedside.

### METHODS:

**Cell proliferation assay:** C2C12 myoblasts and fibroblasts obtained from murine skeletal muscle by using the previously published preplating technique [3], were cultured in 96 well plates (n=5) with DMEM containing 10% FBS, 1% penicillin/streptomycin (P/S), with addition of different concentration of either Angiotensin II (ANG) ( $10^{-12}$  to  $10^{-4}$  M) or LOS ( $10^{-12}$  to  $10^{-4}$  M). CellTiter Cell Proliferation Assay kit (Promega, Madison, WI) was used to measure cell proliferation at 24, 48, and 74 hour after incubation.

**C2C12 cell differentiation assay:** C2C12 myoblasts were cultured in 24 well plates (n=4) with differentiation medium (DMEM supplemented 2% horse serum and 1% P/S) containing different concentration of ANG ( $10^{-12}$  to  $10^{-4}$  M) or LOS ( $10^{-12}$  to  $10^{-4}$  M). Three days after incubation immunocytochemistry of myosin heavy chain was performed and the fusion index (a ratio of the number of nuclei in myotubes/total nuclei) was calculated to assess the effects of ANG and LOS on differentiation capacity of C2C12 myoblast.

**Animal model:** The muscle contusion model was developed in tibialis anterior (TA) muscle of C57BL/6 wild-type mice. Different concentrations of LOS (12.5, 125, 1250, or 4000mg) in 1Liter of tap water were administered beginning immediately after injury until endpoint while the control group drink tap water (six mice in each group). These doses were calculated based on the average fluid intake of mice as 3, 30, 300, and 1000mg/kg/day respectively. Animals were sacrificed and TA muscles were harvested 4 weeks after injury. Muscle samples were then cryosectioned and histological stained (hematoxylin and eosin stain (H&E) and Masson's Trichrome stain). The numbers of centronucleated regenerating myofibers were counted to evaluate the regeneration. Northern Eclipse software (Empix Image, Inc.) was used to quantitate the total cross-sectional area of fibrosis. Statistical analysis was performed with ANOVA and Scheffe's F test as post hoc test. Statistical significance was defined as  $p < 0.05$ .

### RESULTS SECTION:

**LOS enhanced C2C12 myoblast proliferation:** Exposure to  $10^{-12}$  to  $10^{-4}$  M of ANG attenuated C2C12 proliferation after 72hr incubation. Whereas,  $10^{-12}$  to  $10^{-8}$  M of LOS stimulated C2C12 proliferation at the same time point. However, a high concentration of LOS ( $10^{-4}$  M) failed to increase cell growth (Fig. 1). Surprisingly, neither ANG nor LOS had any effect on fibroblast proliferation (not shown).

**LOS stimulated myoblast differentiation:** C2C12 differentiation was inhibited by  $10^{-12}$  M of ANG, however, the effect attenuated at higher concentrations (Fig.2). Likewise,  $10^{-12}$  M of LOS enhanced C2C12 differentiation and the stimulation was dropping while concentrations of LOS increased. It is noteworthy that  $10^{-4}$  M of LOS significantly suppressed differentiation (Fig. 2).

**LOS enhanced muscle regeneration and decreased fibrosis:** We could observe significant increases in number of centronucleated myofibers in the LOS-treated animals when compared with control animals (Fig. 3). The group treated with 300 mg/kg/day of LOS showed the most effective regeneration among groups. The best regeneration

correlated with the group that displayed a significant reduction in fibrosis. However, these beneficial effects decreased when the dose of LOS was increased to 1000 mg/kg/day (Fig. 4).

Figure 1

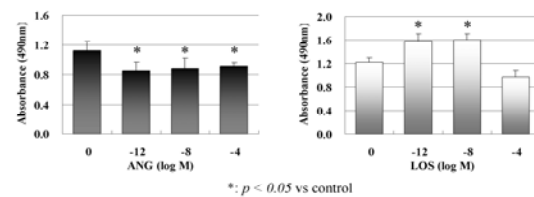


Figure 2

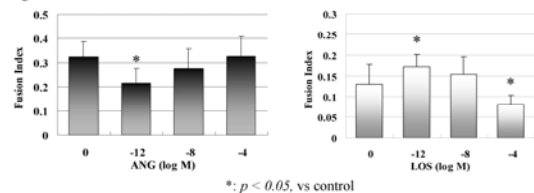


Figure 3

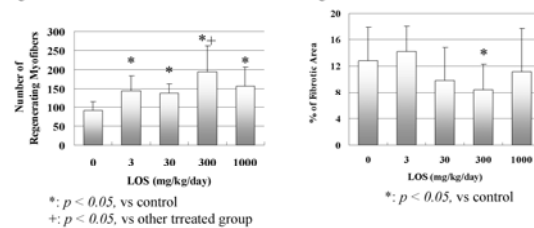
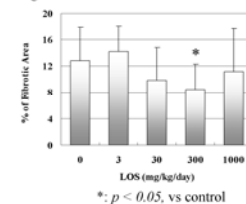


Figure 4



### DISCUSSION:

The biphasic effect of LOS on C2C12 myoblasts *in vitro*, stimulating at low dose while decreasing at high dose, suggested that there is an optimal dose of LOS. Consequently we found that LOS improves skeletal muscle regeneration at 4 weeks after contusion injury, except that these effects were reduced/eliminated in 1000 mg/kg/day group. The best effective dose was 300 mg/kg/day. Overall, these effects of LOS were more pronounced for regeneration than for fibrosis. These *in vivo* results are consistent with our *in vitro* results that LOS was able to exert effects on C2C12 whereas fibroblasts were not affected by either ANG or LOS. Regeneration and fibrosis are two competitive processes after muscle injury; therefore, decreasing fibrosis observed in LOS-treated group is can be the result of the increase regeneration. In other words, LOS might indirectly reduced fibrosis by directly stimulating regeneration. Although there were not statistical differences in fibrosis in lower dose LOS groups (3 and 30 mg/kg/day) as compared to control, these effects of LOS on both regeneration and fibrosis showed similar dose dependent trend. However, *in vivo* results above were obtained only from single time point after injury. Since there are time lags between peaks of myofiber regeneration and fibrosis after injury, further investigations are required to examine the effect of LOS on regeneration and fibrosis at their individual peak time, which will facilitate clinical application of ARBs in improving skeletal muscle healing.

### ACKNOWLEDGEMENTS:

The authors are grateful for technical assistance from Jessica Tebbets, and Aiping Lu. Funding support was provided by a grant from the Department of Defense (W81XWH-06-1-0406).

### REFERENCES:

- Li Y, et al., *Am J Pathol.* 2004;164: 1007-19.
- Bedair HS, et al., *Am J Sport Med.* 2008; 36: 1548-54.
- Qu Z, et al., *J Cell Biol.* 1998; 142: 1257-67.



## Blocking Myostatin Improves Muscle Healing Via Enhancement of Angiogenesis

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### INTRODUCTION

Myostatin (MSTN), a member of the TGF- $\beta$  superfamily, is a powerful inhibitor of skeletal muscle growth [1], and has also been implicated in the formation of fibrosis in injured skeletal muscle [2]. An increase of muscle regeneration and a decrease of fibrosis is observed in the injured muscle of MSTN knockout (MSTN<sup>-/-</sup>) mice when compared to that of injured wild-type (WT) mice [2]. We have also observed similar results when we block MSTN utilizing adeno-associated viral vector to deliver MSTN propeptide (AAV-MPRO) (unpublished data), a natural inhibitor of MSTN [3]. In this study, we investigated whether AAV-MPRO could stably express in vivo and benefit the healing of injured skeletal muscle up to one year after muscle injury. We further examined mechanisms by which the inhibition of MSTN improved skeletal muscle healing after laceration injury. A positive correlation has been reported between angiogenesis and skeletal muscle healing [4]; therefore, we hypothesized that injured MSTN<sup>-/-</sup> muscles and injured muscles transduced with AAV-MPRO would show more angiogenesis than their respective controls.

### METHODS

**Animal experiments:** We injected AAV-MPRO ( $1 \times 10^{11}$  v.g.) in 50  $\mu$ l of PBS into gastrocnemius muscles (GMs) of C57BL/6 WT mice (6-8 weeks old). AAV-GFP was injected into GMs of WT littermates as a control. One month after AAV vector transduction, the GMs of the mice were lacerated. The GMs of 10 mice were harvested at 4 weeks post-injury (n = 5). The remaining mice were sacrifice at 1 year post-injury (n = 4). HE staining was performed to monitor muscle regeneration in the injured muscles. All samples were stored in -80°C.

**Immunohistochemistry:** The muscles were cryosectioned and fixed in formalin. The sections were then incubated with 10% HS for 1 hour after which a rat CD31 (endothelial marker) primary antibody (1:150) was applied along with a mouse anti-fast myosin heavy chain (MyHC) antibody or sheep anti-MPRO antibody, which were incubated for 1 hour at RT. The sections were then washed three times with PBS and incubated with the secondary antibodies rabbit anti-rat conjugated with 555 (red) and anti-mouse conjugated with 488 (green) or anti-sheep-555 (red) for 1h. Nuclei were counter stained with DAPI (blue). We used image J software to measure the number of CD31-positive capillaries to evaluate angiogenesis within the injury site. Student's *t* test was used to determine significance ( $P < 0.05$ ).

### RESULTS

**Expression of GFP and MPRO in skeletal muscle:** One year after AAV transduction, we still detected strong expressions of GFP and MPRO in myofibers of AAV-GFP/MPRO transduced muscles (Fig. 1). MPRO-positive myofibers (arrowheads) indicates constitutive expression of MPRO in skeletal muscle transduced with AAV-MPRO.

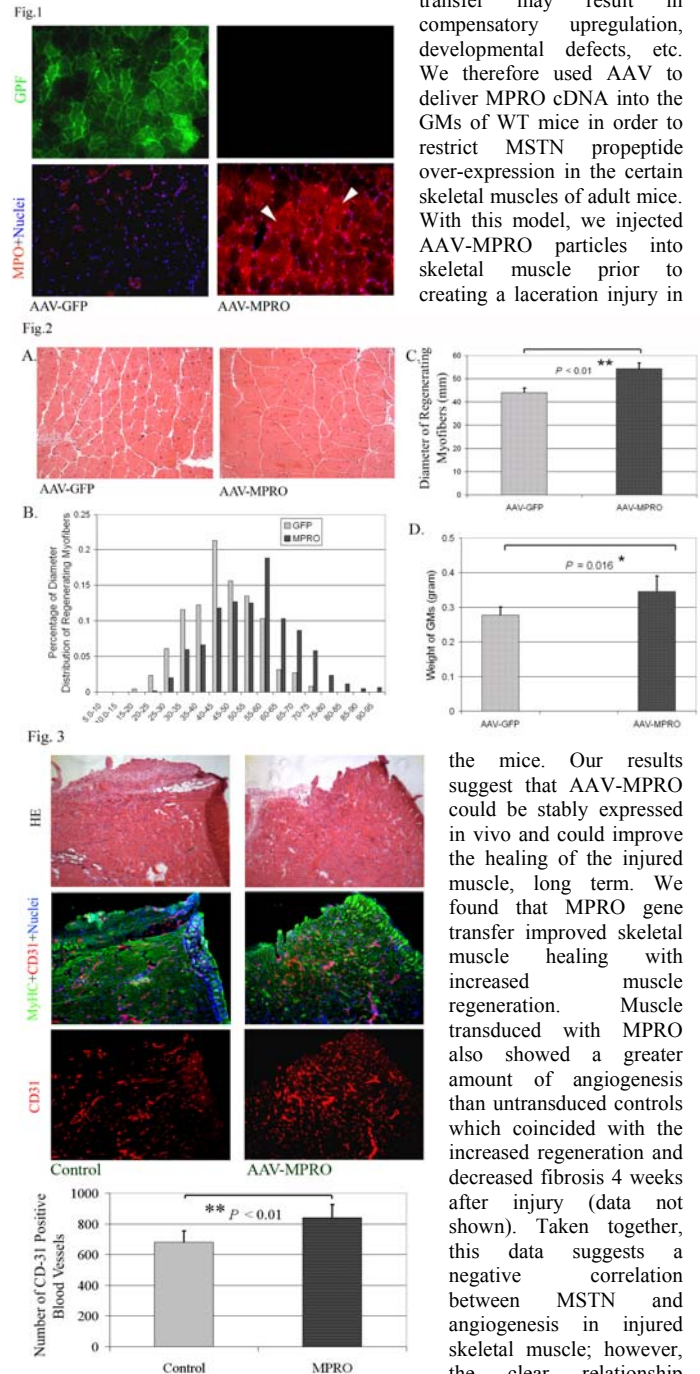
**Improved skeletal muscle healing by MPRO:** We observed significantly larger regenerating myofibers in AAV-MPRO transduced injured muscle than in controls, 1 year post-injury (Fig. 2A, C). Correspondingly, distribution of diameter of regenerating myofibers revealed that AAV-MPRO transduced injured muscle contained a higher percentage of larger diameter regenerating myofibers. For instance, 30% of the diameters of regenerating myofibers in control muscle were larger than 50  $\mu$ m when compared to 61 % of that in AAV-MPRO transduced muscle (Fig. 1B). Blocking MSTN with MPRO led to a significant increase in the weight of the GMs (Fig. 2D).

**Increased angiogenesis in AAV-MPRO-transduced mice after GM laceration:** Fig.3 shows representative images from injured AAV-MPRO transduced muscles and controls. Significantly more CD31-positive capillaries were observed in AAV-MPRO transduced injured muscle than in controls at 4 weeks post-injury (Fig.3).

### DISCUSSION

Our unpublished data show that angiogenesis occurs earlier in the MSTN<sup>-/-</sup> muscle than in normal muscles after laceration injury. At 4 weeks after injury, MSTN<sup>-/-</sup> muscle contained significantly more CD31-positive capillaries than the controls. The increased angiogenesis appears to partially account for improved muscle healing in injured MSTN<sup>-/-</sup> mice. Nevertheless, it is noteworthy that the irreversibility of genetic

transfer may result in compensatory upregulation, developmental defects, etc. We therefore used AAV to deliver MPRO cDNA into the GMs of WT mice in order to restrict MSTN propeptide over-expression in the certain skeletal muscles of adult mice. With this model, we injected AAV-MPRO particles into skeletal muscle prior to creating a laceration injury in



the mice. Our results suggest that AAV-MPRO could be stably expressed in vivo and could improve the healing of the injured muscle, long term. We found that MPRO gene transfer improved skeletal muscle healing with increased muscle regeneration. Muscle transduced with MPRO also showed a greater amount of angiogenesis than untransduced controls which coincided with the increased regeneration and decreased fibrosis 4 weeks after injury (data not shown). Taken together, this data suggests a negative correlation between MSTN and angiogenesis in injured skeletal muscle; however, the clear relationship

between MSTN and angiogenesis warrants further investigation.

### ACKNOWLEDGMENTS

This work was supported by funding from the Henry J. Mankin Endowed Chair for Orthopaedic Research at the University of Pittsburgh, the William F. and Jean W. Donaldson Chair at Children's Hospital of Pittsburgh, the Hirtzel Foundation, and the National Institutes of Health (R01 AR47973 awarded to J.H.).

### REFERENCES

- McPherron AC et al. Nature 1997;387:83-90.
- Zhu J et al. J Biol Chem 2007; 282(35):25852-63.
- Lee SJ et al. Proc Natl Acad Sci USA 2001;98:9306-11.
- Nguyen et al. Neuromuscul Disord. 15 (2):154-63, 2005.

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# Angiotensin Receptor Blocker Improves Skeletal Muscle Function Recovery in a Dose Dependent Manner

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## INTRODUCTION:

Muscle injuries are very common musculoskeletal problem encountered in sports medicine. Although these injuries are capable of healing, complete functional recovery is hindered by the formation of dense scar tissue triggered by TGF- $\beta$ 1 [1]. We have previously reported that Losartan (LOS), one of the Angiotensin II Receptor Blockers (ARBs) FDA approved for antihypertensive treatment, has been shown to improve muscle healing through antifibrotic action [2]. We also demonstrated that specific doses of LOS (30 mg/kg/day and higher) improved muscle regeneration and attenuated the development of pathological fibrosis when were administrated immediately after injury [3]. In this study, we investigated whether LOS can improve muscle strength recovery after contusion injury, and also attempted to understand the mechanism of LOS action by analyzing gene expression of myostatin and follistatin, which are considered important regulators of skeletal muscle growth.

## METHODS:

**Animal model:** The muscle contusion was developed in tibialis anterior (TA) muscle of C57BL/6 wild-type mice. Different concentrations of LOS (12.5, 125, 1250, or 4000mg dissolved in 1 liter of tap water) were administered to animals immediately after injury (n=6 in each group). These doses were calculated based on the average fluid intake of mice as 3, 10, 30, 300 mg/kg/day respectively. The control-injured mice received tap water. After 4 weeks animals were sacrificed to evaluate the healing.

**Physiological testing:** Under general anesthesia, the TA distal tendon was exposed and tied securely to a lever arm of transducer. Peroneal nerve was electrically stimulated and the specific peak twitch and tetanic force developed by TA muscle was monitored. All data were digitally recorded and stored until evaluation.

**Quantitative Real-time PCR:** Total RNA was extracted from muscle tissues using Nucleospin RNA kit (Clontech). cDNA was synthesized with SuperScriptTM II reverse transcriptase (Invitrogen), according to manufacturer's instructions. cDNAs and primers were added to SYBR Green PCR master mix (Applied Biosystem) according to manufacturer's instructions. The quantitative analysis for follistatin and myostatin gene expression was performed. All data were normalized to cyclophilin which was used as the internal control.

**Statistical analysis:** The results were expressed as the mean  $\pm$  SD. To determine minimum effective dose of LOS in physiological testing, we analyzed the results using Williams' multiple comparison. The differences of mean specific twitch and tetanic force between control muscle (injured/non-treated) and normal muscle (non-injured) were analyzed with student t-test. Differences of gene expression between samples were assessed by the ANOVA and Tukey's test as post hoc test. Statistical difference was defined as  $p < 0.05$ .

## RESULTS SECTION:

**Improvement of Muscle Strength:** LOS improved TA muscle force recovery after contusion injury. Specific peak twitch force and tetanic force was elevated in mice receiving high dose of LOS (30 and 300 mg/kg/day) in comparison to the animals receiving low dose of LOS (3 and 10 mg/kg/day) (Figure 1).

**Myostatin gene expression:** Expression of myostatin in the injured TA muscle in the control-injury and low dose of LOS treatment groups was lower than in the normal TA muscle, while there was no difference between normal and high dose of LOS treatment groups. Expression of follistatin in the control group was higher than in normal muscle and low dose of LOS treatment groups. The highest expression of follistatin was observed in the 30 mg/kg/day of LOS treatment group and it was significantly higher compared to the control group (Figure 2).

Figure 1

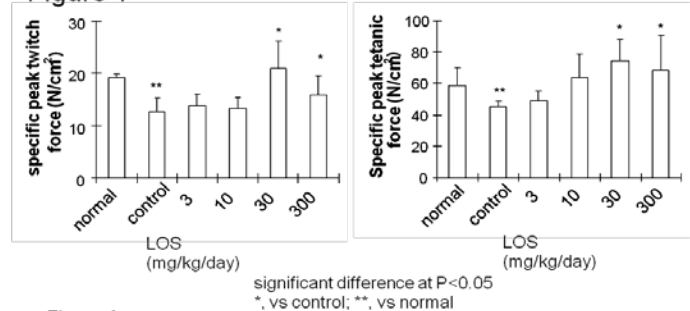
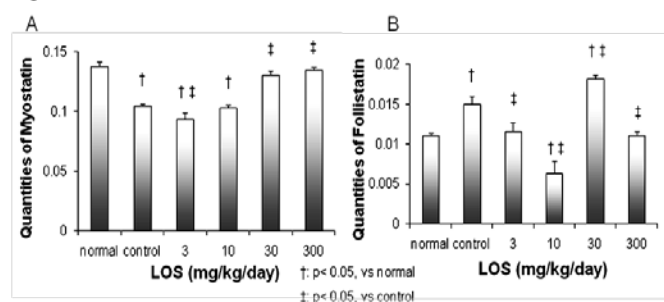


Figure 2



## DISCUSSION:

Functional recovery is the most important factor in the skeletal muscle healing after injury. Here we demonstrate that LOS administration immediately after injury improves recovery of skeletal muscle strength. These results also support our previous histological findings [3]. We believe that the mechanism of muscle regeneration after injury might be related to the expression of follistatin, positive regulator of skeletal muscle growth. We noticed over expression of follistatin in the 30 mg/kg/day treatment group compared to the normal and control-injury groups. These findings correlate with the results of physiological testing. It is unclear why the 30 mg/kg/day LOS display on increase expression of myostatin, negative regulator of skeletal muscle growth. Our results suggest that continuous administration of the high dose of LOS, in particularly 30 mg/kg/day, immediately after skeletal muscle injury could accelerate skeletal muscle functional recovery. We aimed to evaluate only single time point of LOS administration immediately after injury. Further studies are required to determine biological effect of LOS and facilitate clinical application of ARBs for improvement of skeletal muscle healing.

## ACKNOWLEDGEMENTS:

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## REFERENCES:

- Li Y, et al., *Am J Pathol.* 2004;164: 1007-19.
- Bedair HS, et al., *Am J Sport Med.* 2008; 36: 1548-54.
- Uehara K, et al., 55th Annual Meeting of the Orthopaedic Research Society, 2009.

## Angiotensin II Receptor Blocker Ameliorates Skeletal Muscle Healing

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### INTRODUCTION:

Muscle injuries are very common musculoskeletal problem encountered in sports medicine. Although these injuries are capable of healing, complete functional recovery is hindered by the formation of dense scar tissue triggered by TGF- $\beta$ 1 [1]. Losartan (LOS) is a FDA approved antihypertensive medication and has a well-tolerated side-effect profile. Our previous study revealed that 30 mg/kg/day of LOS treatment was effective in promoting muscle healing and inducing antifibrotic effect in a murine model of skeletal muscle after injury [2,3]. However, the effective dose (30 mg/kg/day) which was administrated immediately after muscle injury is higher compared to the dose used in human (10 mg/kg/day). In this study we investigated the effect on muscle healing in a murine animal model using human dose of LOS (10 mg/kg/day) administered at different time after injury.

### METHODS:

**Animal model:** The muscle contusion model was developed in tibialis anterior (TA) muscle of C57BL/6J wild-type mice. The administration of 125 mg of LOS dissolved in 1 liter of tap water was started on day 0, 3, 7 and 14 after injury and continued for 4 weeks. Tap water without LOS was given to the animals in control-injury group (6 mice in each group). The LOS dose taken was calculated based on the average fluid intake of mice [3]. Four weeks after injury, we performed physiological testing and harvested the TA muscle for histology.

**Physiological testing:** Under general anesthesia, the TA distal tendon was exposed and tied securely to a lever arm of transducer. Peroneal nerve was electrically stimulated and the specific peak twitch and tetanic force developed by TA muscle was monitored. All data were digitally recorded and stored until evaluation.

**Histology:** TA muscles harvested 4 weeks after injury were cryosectioned and stained for hematoxylin and eosin (H&E) and Masson's Trichrome stain. The number of centronucleated regenerating myofibers was counted to evaluate muscle regeneration. Northern Eclipse software (Empix Image, Inc.) was used to analyse the total cross-sectional area of muscle fibrosis.

**Quantitative Real-time PCR:** Total RNA was extracted from muscle tissues using Nucleospin RNA kit (Clontech). cDNA was synthesized with SuperScript<sup>TM</sup> II reverse transcriptase (Invitrogen), according to manufacturer's instructions. cDNAs and primers were added to SYBR Green PCR master mix (Applied Biosystem) according to manufacturer's instructions. The quantitative analysis for Follistatin (FSTN) and Myostatin (MSTN) gene expression was performed. All data were normalized to cyclophilin which was used as the internal control.

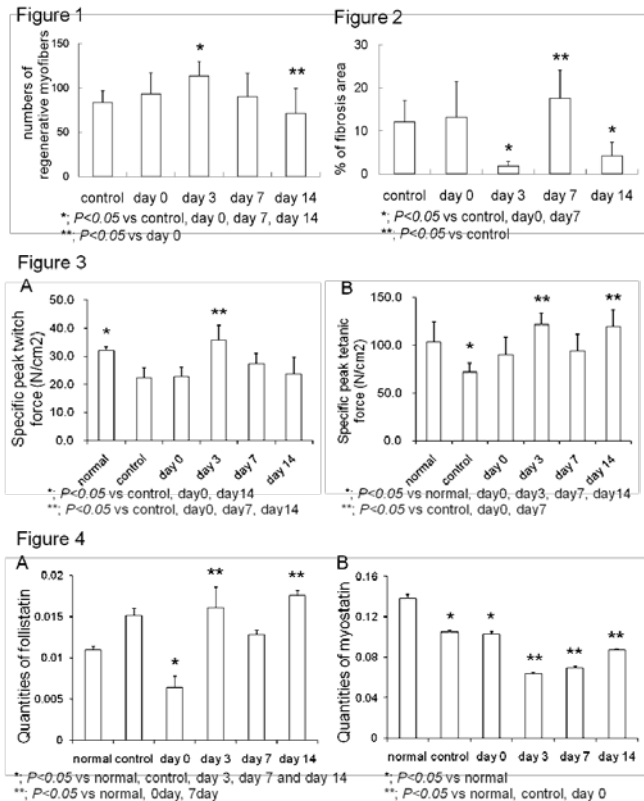
**Statistical analysis:** Differences between samples were assessed by the ANOVA and Scheffe's F test as post hoc test. Statistical significance was defined as  $p < 0.05$ .

### RESULTS:

**LOS enhanced muscle regeneration and reduced fibrosis:** We observed significant increases in the number of centronucleated myofibers in the day 3 treatment group when compared with other treatment groups (Fig. 1). The highest effect on muscle regeneration coincided with significant decrease of fibrosis in the day 3 treatment group (Fig. 2).

**LOS enhanced muscle force:** LOS improved muscle strength recovery after contusion injury. Specific peak twitch force and peak tetanic force was significantly greater in mice treated with LOS beginning at day 3 after injury (Fig. 3).

**LOS enhanced expression of Follistatin and Myostatin:** Expression of FSTN detected by RT-PCR in the day 3 and day 14 LOS treatment groups was greater than in the normal non-injured or LOS treated at day 0 and day 7 groups (Fig. 4A). Expression of MSTN in the day 3, day 7 and day 14 LOS treatment groups was lower than in the normal, control and day 0 LOS treatment groups (Fig. 4B). The highest expression of FSTN coincided with the lowest expression of MSTN in the day 3 LOS treatment group.



### DISCUSSION:

Our study revealed that the most effective timing for administration of human dose of LOS (10 mg/kg/day) was 3 days after muscle injury. We observed increased number of centronucleated myofibers and decreased area of fibrosis when LOS was administered at day 3 after injury. The functional recovery after skeletal muscle injury is the most important factor for clinical translation of this therapy. We demonstrate that enhancement of muscle strength in day 3 LOS treatment group correlates with the improvement of muscle regeneration and the reduction of fibrosis. We have previously reported that muscle regeneration and fibrosis formation are two concomitant processes after muscle injury, and the effect of LOS was more prominent on muscle regeneration than on fibrosis [3]. Our study supports this finding. In addition, it may suggest that administration of LOS effectively leads to enhanced muscle regeneration after muscle injury via down regulation of endogenous MSTN, negative regulator of skeletal muscle growth. A decrease in FSTN expression was also observed in the day 3 LOS treatment group which may be related to the decrease in MSTN expression. In summary, we indicate that 10 mg/kg/day (human safety dose) of LOS treatment initiated at 3 days after contusion injury can enhance structural and functional healing in mouse skeletal muscle.

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### REFERENCES:

- Li Y, et al., *Am J Pathol.* 2004; 164: 1007-19.
- Bedair HS, et al., *Am J Sport Med.* 2008; 36: 1548-54.
- Uehara K, et al., 55th Annual Meeting of the Orthopaedic Research Society, 2009.



**Improving Recovery Following Recurrent Hamstring Injury  
Using an Angiotensin II Receptor Blocker: Two Case Studies**

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## Improving Recovery Following Recurrent Hamstring Injury Using an Angiotensin II Receptor Blocker: Two Case Studies

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### INTRODUCTION

Hamstring muscle injuries are common in young competitive athletes. A recent study on National Football League training camp injuries reports hamstring injuries were the most common among muscle strain as well as the most severe. Recurrence is common, secondary to the pressure to return to play prior to complete healing of the injury, with a higher re-injury rate than any other type of injuries. Although muscles can undergo regeneration after injury, the healing process is slow and often culminates in incomplete functional recovery and formation of fibrosis.

A growing understanding of the cellular and molecular events that commonly occur during fibrosis in various tissues, including skeletal muscle, has provided a strong foundation for the development of effective therapies to prevent fibrosis and improve tissue healing. Because TGF- $\beta$ 1 plays such a crucial role in tissue fibrosis, particularly in skeletal muscle, it warrants attention as a key target for anti-fibrotic applications. Of the agents to block TGF- $\beta$ 1, Losartan potassium, a non-peptide molecule that works as an angiotensin II receptor blocker, is particularly attractive for clinical application as it is FDA approved and has minimal side effects. In a murine model, we have found that angiotensin receptor blocker-treated mice exhibited a histological, dose-dependent improvement in muscle regeneration and a significant reduction in fibrous tissue formation within the area of injury.

Given that Losartan has already been used clinically with an extremely safe side effect profile, we have conducted two case studies in young college athletes that sustained recurrent hamstring injuries and whose recoveries were safely improved with losartan. This is an off-label use of losartan (i.e.: the FDA has not approved labeling the device for the described purpose). Here we report the results obtained.

### METHODS

Both subjects were submitted to the same protocol that is herein described: after obtaining the subjects' informed consent for treatment, both subjects were started on a 30-day treatment course of losartan at the manufacturer's recommended oral dose of 50 mg per day. Both subjects were healthy and had none of the contra-indications for the use of losartan. In addition to the medication, they underwent a routine rehabilitation program that gradually progressed to eccentric strengthening. The subjects reported no side effects while they were taking the study medication and remained normotensive throughout.

They were initially evaluated by clinical examination and were subsequently evaluated every 7 days with serial measurements (with a hand-held dynamometer - Lafayette Instrument Inc) of hamstring flexibility and strength as well as their blood pressure. Prior to the start of the medication the subjects were submitted to a magnetic resonance imaging (1.5T; GE-Sigma, Waukesha, WI, USA). After a period of 11 weeks the subjects underwent an isokinetic test (Biodex II) to better evaluate muscle strength compared to the non-injured side.

### RESULTS

#### - Subjects

**Subject #1:** male, 21 years old, college athlete (football punter). He presented 10 days after an acute onset of "searing" pain in his left

posterior thigh when he was kicking with his left leg. He referred a similar injury 5 weeks prior to the present injury.

**Subject #2:** male, 22 years old, college athlete (Ultimate Frisbee). He presented 4 days after an acute onset of pain in his left posterior thigh while he was sprinting. He referred two previous hamstring injuries (2 and 7 months prior to the present injury).

#### - MRI results (at time of injury)

**Subject #1:** Acute Grade 2 hamstring strain was observed with a partial thickness tear of the biceps femoris at the proximal myotendinous junction with surrounding edema without an associated avulsion fracture or hematoma.

**Subject #2:** Grade 2 strain with partial thickness tear of the left biceps femoris at the mid aspect, extends approximately 6 cm in the craniocaudal dimension.

#### - Hamstring flexibility and strength

**Subject #1:** By the third week after the injury, no deficit was evident in hamstring flexibility. By the ninth week, the isometric hamstring strength measurements at 30 and 90 degrees of knee flexion were 92 and 84% than the uninjured side respectively (Fig.1).

**Subject #2:** Also, by the third week after the injury, no deficit was evident in hamstring flexibility. By the ninth week, the injured side had a higher isometric hamstring strength measurement at 30 and 90 degrees of knee flexion. They were 132% and 110% than the uninjured side respectively (Fig.1).

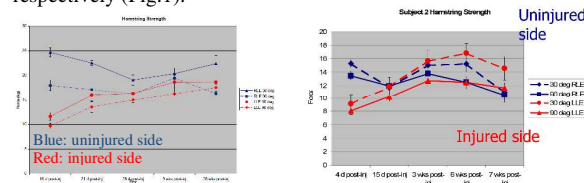


Figure 1: Isometric Hamstring strength (Kg)

#### - Isokinetic testing results

**Subject #1:** Eleven weeks after the injury, an isokinetic test of the hamstrings was performed showing an essentially normal result. Peak hamstring torque, on the uninjured side, was 96% of the injured side at 60 degrees per second and 107% of the injured side at 180 degrees per second.

**Subject #2:** Thirteen weeks after the injury, an isokinetic test of the hamstrings was performed showing an essentially normal result. Peak hamstring torque of the injured side was 96.3% compared to the uninjured side at 60 degrees per second and 97.3% of the uninjured side at 180 degrees per second.

### DISCUSSION / CONCLUSION

We have described use of losartan, which is an FDA-approved angiotensin II receptor blocker, to treat two healthy collegiate athletes with a grade 2 biceps femoris injury. The patients tolerated the course of losartan well with no hypotension or any other side effects. Additionally, the patients demonstrated recovery of normal flexibility and strength compared to the contra-lateral leg. Both subjects were ready for return to sports in 9 to 11 weeks after injury.

### ACKNOWLEDGEMENTS

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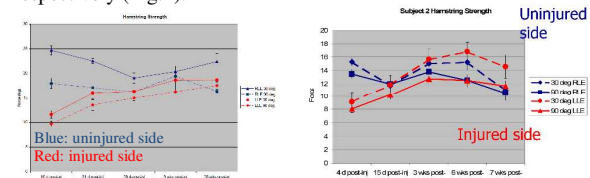


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# **Follistatin Improves Skeletal Muscle Healing After Injury & Disease Through an Interaction with Muscle Regeneration, Angiogenesis and Fibrosis**

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## **Running head: Follistatin Improves Skeletal Muscle healing**

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## Abstract

Recovery from skeletal muscle injury is often incomplete due to the formation of fibrosis and inadequate myofiber regeneration; therefore, injured muscle could benefit significantly from therapies that both stimulate muscle regeneration and inhibit fibrosis. To this end, we have focused on blocking myostatin, a member of the TGF- $\beta$  superfamily and a negative regulator of muscle regeneration, with the myostatin antagonist follistatin. *In vivo*, follistatin over-expressing transgenic mice underwent significantly greater myofiber regeneration and had less fibrosis formation compared to wild type mice after skeletal muscle injury. Follistatin's mode of action is likely due to its ability to block myostatin and enhance neovascularization. Furthermore, muscle progenitor cells isolated from follistatin over-expressing mice were significantly superior to muscle progenitors isolated from wild type mice at regenerating dystrophin positive myofibers when transplanted into the skeletal muscle of dystrophic mdx/SCID mice. *In vitro*, follistatin stimulated myoblasts to express MyoD, Myf5, and myogenin, which are myogenic transcription factors that promote myogenic differentiation. Moreover, follistatin's ability to enhance muscle differentiation is at least partially due to its ability to block myostatin, activin A and transforming growth factor- $\beta$  1, all of which are negative regulators of muscle cell differentiation. Our study suggests that follistatin is a promising agent for improving skeletal muscle healing after injury and muscle diseases such as the muscular dystrophies.

## Introduction

Although skeletal muscle injuries are extremely common, accounting for up to 35% to 55% of all sports-related injuries, the treatments that are currently available have not progressed over the last few decades and are often ineffective. Unfortunately, there is significant morbidity associated with these injuries, such as the development of painful contractures, loss of muscle extensibility and strength, and the increased risk for repeated injury, which is largely due to extensive fibrosis formation. In response to traumas and disease, the local secretion of transforming growth factor- $\beta$  1 (TGF- $\beta$ 1), a potent fibrotic cytokine, induces the formation of fibrosis in various tissues and organs including skeletal muscles<sup>1-9</sup>. Various agents, including suramin<sup>10-11</sup>,  $\gamma$ -interferon<sup>12</sup>, decorin<sup>5, 8, 13-15</sup>, relaxin<sup>16-17</sup>, and losartan<sup>9, 18</sup>, have been shown to significantly enhance skeletal muscle regeneration and reduce fibrosis in injured muscles, and in a broad spectrum of myopathic diseases, partially by blocking TGF- $\beta$ 1. Although much of the pathogenesis following skeletal muscle injury has been attributed to TGF- $\beta$ 1 expression, it has become clear that myostatin, a member of TGF- $\beta$  superfamily, can also be implicated in the formation of muscle fibrosis<sup>19-24</sup>. Myostatin was initially known as a primary negative regulator of the growth and development of fetal and postnatal skeletal muscle<sup>25-26</sup>. A variety of approaches to block myostatin function, including the creation of a myostatin gene knockout animal model, the use of a myostatin neutralizing antibody, and the delivery of the myostatin propeptide (MPRO) gene, via an adeno-associated virus (AAV), have unequivocally shown that the inhibition of myostatin reduces fibrosis and enhances muscle regeneration in both injured and dystrophic murine skeletal muscles<sup>19-24</sup>. It has been shown that myostatin directly stimulates the formation of skeletal muscle fibrosis by stimulating muscle fibroblasts, whose excessive activities are responsible for the development of fibrosis in injured muscle<sup>23, 27</sup>. Muscle fibroblasts express the myostatin protein<sup>23, 27</sup> and its receptor, ACVR2B<sup>27</sup>. Myostatin increases the proliferation and secretion of extracellular matrix products by muscle fibroblasts<sup>23, 27</sup>. These effects may be due to the

activation of the canonical TGF- $\beta$  signaling pathway, as well as the PI3K/Akt/mTOR pathway in muscle fibroblasts, as evidenced by increased phosphorylation of SMAD2/3 and Akt/mTOR, respectively<sup>27</sup>. Injection of myostatin-coated beads into skeletal muscle leads to the formation of fibrosis around the injected beads, which could be reversed with the addition of follistatin, an antagonist of myostatin<sup>27</sup>. It has also been observed that myostatin and TGF- $\beta$ 1 reciprocally induce the expression of one another<sup>23, 28</sup>. When TGF- $\beta$ 1 signaling is blocked, it impairs myostatin's biological activity, and vice versa, which suggests that TGF- $\beta$ 1 acts synergistically with myostatin to induce fibrosis in injured skeletal muscle<sup>23</sup>.

In addition to impairing skeletal muscle healing by promoting fibrosis, myostatin also inhibits myofiber regeneration in mouse models that mimic diseases such as Duchenne muscular dystrophy (DMD)<sup>22</sup>, amyotrophic lateral sclerosis-associated muscular atrophy<sup>29</sup>, as well as after experiencing a traumatic injury<sup>20, 23</sup>. Specifically the diaphragm muscles of mdx mice, an animal model of DMD, were noted to undergo significantly more myofiber damage and less myofiber regeneration when compared to transgenic mdx mice that also had their myostatin gene knocked out<sup>22</sup>. Similarly, in two acute muscle injury models, the first where the tibialis anterior muscle was injured by the injection of notexin, and the other where the gastrocnemius muscle (GM) was injured via laceration, there was significantly greater regeneration and significantly less fibrosis formation in the injured myostatin knockout mice than the injured wild type (WT) controls<sup>20, 23</sup>. Given the promising benefits of blocking myostatin in skeletal muscle, a safety trial using MYO-29, a neutralizing antibody of myostatin, was conducted in adult patients with various forms of muscular dystrophy including: Becker muscular dystrophy, facioscapulohumeral dystrophy, and limb-girdle muscular dystrophy<sup>30</sup>. The results of this trial demonstrated that the patients could tolerate MYO-29 very well when it was administrated systemically<sup>30</sup>.

Research into the development of therapies to antagonize myostatin has led to the discovery of several new functions exhibited by follistatin. Follistatin was originally found to antagonize activin A in reproductive tissues and was also observed to neutralize several other

proteins within the TGF- $\beta$  superfamily<sup>31-33</sup>. Follistatin is also well-known as a potent myostatin antagonist in skeletal muscle<sup>34-35</sup>. While follistatin over-expressing transgenic mice exhibit a dramatic increase in muscle mass, much as is seen to occur in myostatin knockout mice<sup>35</sup>, several *in vivo* studies on follistatin have shown that the systemic administration of this agent directly inhibits myostatin and also reduces myostatin-induced muscle wasting<sup>26, 34, 36</sup>. Moreover, a single injection of AAV-mediated follistatin into the quadricep and tibialis anterior muscles, of both young and aged WT C57BL/6J or dystrophic mice, increased the muscles weight, and more interestingly, it also promoted an increase in the weight of non-injected muscles located remotely (e.g., triceps). This increase in muscular weight was accompanied by an increase in hindlimb grip strength. It is also noteworthy that increased follistatin levels were not found to be detrimental to the reproductive capacity of the treated animals.<sup>37</sup> Apart from these animal model findings, it has also been reported that follistatin plays a beneficial role in human myoblast transplantation. Human myoblasts over-expressing follistatin outperformed normal human myoblast controls, in both proliferation and differentiation capacities *in vitro*, and regenerated much larger engraftment areas when injected into the tibialis anterior muscles of SCID mice<sup>38</sup>. Importantly, the safety and effectiveness of follistatin treatment has been evaluated in nonhuman primates<sup>39</sup>, where it has been shown that the long-term expression of AAV-mediated follistatin, in the quadriceps of cynomolgus macaque monkeys, increased their muscle mass and strength without having any deleterious effects on critical organ systems<sup>39</sup>. This minimal off-target effect makes this molecule a promising potential therapeutic agent to treat muscles injured acutely and through degenerative muscle disorders; however, before translating follistatin-based therapies from the bench to the bedside, clear mechanisms of how follistatin promotes muscle regeneration requires extensive investigation.

In this report, we provide *in vivo* and *in vitro* data to support the application of follistatin as a potential therapeutic agent to enhance skeletal muscle healing after injury and disease. In



addition, we investigated the underlying mechanisms of action that follistatin has on muscle cell regeneration, angiogenesis and fibrosis formation. Specifically, we show that follistatin over-expressing transgenic mice undergo more efficient skeletal muscle regeneration while developing less fibrosis after muscle injury (laceration) compared to WT controls. This enhancement of muscle healing in follistatin over-expressing mice after injury appears to be related, at least in part, to an increase in the myogenic potential of muscle progenitor cells, likely due to follistatin's inhibition of myostatin, activin A, and TGF- $\beta$ 1. Finally, we also performed experiments to determine how follistatin impacts the expression and downstream signaling of TGF- $\beta$ 1, as well as the expression of a variety of myogenic transcription factors.

## **Materials and methods**

### ***Animal model***

#### *Comparison of muscle healing between WT and follistatin over-expressing mice after injury*

All animal experiments were approved by the Children's Hospital of Pittsburgh's Institutional Animal Care and Use Committee. We performed partial cross-sectional lacerations on the gastrocnemius muscles (GMs), of 23 male C57BL/6 WT (Jackson Laboratories, Bar Harbor, ME) and 23 male follistatin over-expressing mice (All mice were 7-8 weeks of age) according to a previously published protocol<sup>11-14, 17, 23</sup>. The muscles were then harvested at 1 (n = 3), 2 (n = 8), and 4 (n = 8) weeks and at 1.5 years (n = 4) after creating the laceration injury. Each of the harvested muscles had the percentage of fibrosis and muscle regeneration quantified, as previously described<sup>23</sup>. Briefly, following the cryosectioning of these muscles histological staining was performed with a Masson's trichrome kit (IMEB Inc., Chicago, IL). The amount of fibrosis formation in each of the muscles was measured by selecting three representative and non-adjacent sections and photographing up to 3 microscopic fields (20X). Images were taken for

each section to insure that the entire muscle section was completely photographed. We then pieced the images together in Adobe® Photoshop® CS3 and quantified the percentage area of fibrosis using Northern Eclipse software (Empix Imaging, Inc., Cheektawaga, NY) by measuring the area of fibrotic tissue along the sites of injury and then dividing this area by the total cross-sectional area of the entire tissue section.

In order to evaluate skeletal muscle regeneration, we stained sections from each harvested muscle with Hematoxylin and Eosin (H&E). For each sample, three non-consecutive sections were chosen in each section and images were taken from 2 to 5 microscopic fields (100x) and then pieced together, as described above, to make sure the entire injured area was covered. The smallest diameters of centro-nucleated myofibers, which represent newly regenerating muscle fibers, were quantified with Northern Eclipse software. This technique of measuring the smallest diameters of the centro-nucleated myofibers is a widely used method for evaluating muscle regeneration<sup>22-23, 26, 37, 40-41</sup>. The diameters of more than 350 non-consecutive centro-nucleated myofibers were measured in each of the GMs. Moreover, the percentages of the regenerating myofibers were also determined in each of the injured muscles at all time points.

Additionally, we performed immunohistochemistry to detect myostatin, activin A, collagen type IV, phosphorylation of SMAD2/3 in each of the injured GMs. We also stained for CD31, which is an endothelial cell marker that we used as an index of neo-angiogenesis in the injured muscles, via immunohistochemical staining. The CD31-positive structures were counted using Northern Eclipse software.

#### *Intramuscular injection of AAV2-MPRO/GFP into WT mice*

Twenty male C57BL/6J WT mice (8 weeks old, Jackson Laboratories) were used for these experiments. Fifty  $\mu$ l of AAV serotype 2 (AAV2)-MPRO ( $2.5 \times 10^{12}$  v.g./ml) was injected into both GMs of 10 mice. The same dose of AAV2-GFP was injected into the GMs of 10 additional mice as controls. One month after AAV2 vector injection, both GMs of each mouse were

subjected to laceration injury. The mice were sacrificed 4 weeks after creating the laceration injury and muscle regeneration and fibrosis were measured as described previously for the follistatin over-expressing and WT mice.

### ***Fluorescence immunostaining***

Frozen GMs were sectioned at a thickness of 10  $\mu\text{m}$  and immunohistochemical analysis was then performed to detect myostatin, activin A, collagen type IV, and phosphorylation of SMAD2/3. Tissue sections were fixed in 4% formalin for 5 minutes followed by two 10-minute washes with PBS. The sections were first incubated with 10% horse serum (HS, Vector Laboratories, Burlingame, CA) for 1 hour to block nonspecific staining. Goat anti-myostatin, activin A (R&D Systems, Minneapolis, MN), p-SMAD2/3 (Santa Cruz Biotechnology, Inc.) or rabbit anti-collagen IV (Meridian, Saco, ME) primary antibody were diluted 1:100 in 2% HS in PBS and incubated on the sections overnight at 4°C. Sections were then washed three times with PBS and incubated with a secondary antibody, anti-goat/rabbit IgG conjugated with biotin (1:200) (Vector Laboratories), for 1 hour at room temperature (RT), followed by a PBS wash. Finally, streptavidin conjugated with Alexa Fluor® 555 or 488 (1:500) (Invitrogen, Carlsbad, CA) was applied to each section for an additional hour. DAPI (4', 6-Diamidino-2-phenylindole dihydrochloride; Sigma, St Louis, MO) was used to counter-stain the nuclei. We then quantified the amount of myostatin expression that was present in the injured muscles using Northern Eclipse software, which measures the area and intensity of the detected antibody of interest's signal along the sites of injury. This was then divided by the total cross-sectional area of the tissue to calculate the percentage of the injured muscle tissue that was positive for the detected antibody of interest. The negative controls were stained using the same procedure but without the primary antibody.

To monitor angiogenesis, we first incubated the sections with 10% HS for 1 hour, and then incubated with a rat CD31 primary antibody (BD Biosciences, San Jose, CA) that was

diluted 1:150 in 2% HS in PBS. This preparation was incubated for 1 hour at RT. The sections were then washed three times with PBS and incubated with the secondary antibody, rabbit anti-rat IgG conjugated with Alexa Fluor® 555 (Invitrogen) for 30 minutes. Finally, DAPI was used to counter-stain the nuclei.

### ***Muscle progenitor cell isolation and transplantation into skeletal muscle:***

Using a modified preplate technique<sup>42-43</sup>, we isolated a fraction of muscle progenitor cells (MPCs) with properties of low adhesion to collagen and long-term proliferation. Briefly, we determined the sex of the neonatal mice by anatomically sexing them and then isolated five populations of WT MPCs from 5 male neonatal C57BL/6J mice, and also isolated 7 populations of follistatin over-expressing MPCs from 7 male neonatal follistatin over-expressing mice. These cells were expanded in proliferation medium consisting of Dulbecco's modified Eagle's medium (DMEM; Invitrogen), 10% HS (Invitrogen), 10% fetal bovine serum (FBS; Invitrogen), 1% penicillin/streptomycin (P/S; Invitrogen), and 0.5% chicken embryo extract (Accurate Chemical & Scientific Corporation, Westbury, NY).

After the MPC populations were expanded *in vitro*, MPCs were injected into the GMs of female mdx/SCID mice. These mice were created by crossbreeding mdx (C57BL/10ScSn-Dmdmdx) and SCID (C57BL/6J-prkdcscid/SzJ) mice (Jackson laboratory) at our institution's animal facility. Approximately  $3 \times 10^5$  cells from each cell population were transplanted into the GMs of 4 female mdx/SCID mice. All mdx/SCID mice were sacrificed 2 weeks post-transplantation. The recipient GMs from these mice were harvested at this time, snap-frozen, and cryosectioned at a later date at a thickness of 10  $\mu$ m per section.

Each section was immunostained for dystrophin with a rabbit anti-mouse dystrophin antibody in order to monitor the number of dystrophin positive myofibers formed by the donor MPCs. The tissue sections were first fixed in 5% formalin for 5 minutes, followed by two 10-minute washes with PBS. The sections were blocked with 10% donkey serum for 1 hour, and then

incubated overnight at 4°C with a rabbit dystrophin primary antibody (Abcam, Cambridge, MA) that was diluted 1:500 in 5% donkey serum in PBS. The following day, these sections were washed three times with PBS and incubated with the secondary antibody, donkey anti-rabbit IgG conjugated with Alexa Fluor® 594 (Invitrogen). Images (200x) of the sections representing the largest dystrophin-positive engraftment areas in up to 10 microscopic fields were taken for each sample. Images were spliced together in order to cover the entire engraftment area as shown in Figure 5C. Dystrophin-positive myofibers were then counted to assess the efficiency of cell transplantation in the skeletal muscle of the mdx/SCID mice.

### ***Flow cytometry***

In order to characterize WT and follistatin over-expressing MPC populations, we utilized flow cytometry using antibodies specific for CD34 and Sca-1 on both WT and follistatin over-expressing MPCs to analyze the percentage of stem cells in the MPC populations as previously described<sup>42-43</sup>. Briefly, cultured cells were trypsinized, centrifuged, and washed twice with PBS. We subsequently re-suspended our cell pellets, blocked them with 10% mouse serum (Sigma) for 10 minutes on ice and then applied rat anti-mouse monoclonal conjugated antibodies (CD34-PE, Sca-1-APC; BD Biosciences) and incubated on ice for 30 minutes. Following this incubation period, we excluded nonviable cells by adding 7-amino-actinomycin D (7-AAD; BD Biosciences) to each sample. Cells were then evaluated with a FACS Caliber flow cytometer (Becton Dickinson) and analyzed with CellQuest software (Becton Dickinson).

### ***Cell culture***

A C2C12 myoblast cell line (ATCC, Manassas, VA) was seeded overnight onto collagen-coated 12-well plates in normal growth medium (10% FBS and 1% PS in DMEM). The next day, this medium was replaced with low-serum medium (2% HS and 1% P/S in DMEM), which promotes the myogenic differentiation of myoblasts, supplemented with different combinations of the



recombinant proteins outlined below. The medium and recombinant proteins were changed every 48 hours.

In the first set of experiments, C2C12 myoblasts were stimulated with follistatin recombinant protein (Sigma, St. Louis, MO) and cultured for up to 4 days. The effect of follistatin on myogenic differentiation and expression of MyoD, Myf5, myogenin, and myostatin were examined by myosin heavy chain (MyHC) immunostaining and western blot analysis.

In the second set of experiments, C2C12 myoblasts were stimulated with a combination of follistatin, activin A, and myostatin. The myogenic differentiation of these cells was then evaluated via MyHC immunostaining by calculating the fusion index (i.e., the ratio of nuclei in myotubes to all nuclei) according to a previously published protocol<sup>23</sup>. Images of 5 representative microscopic fields were taken of each well from the 12-well plates.

In the final set of experiments, we incubated C2C12 myoblasts with varying concentrations of the recombinant proteins follistatin and TGF- $\beta$ 1. The cells were then either cultured for 4 days and stained for MyHC to check their myogenic differentiation capacity or cultured 16 hours prior to collecting the cells to analyze them for TGF- $\beta$ 1, SMAD2, and p-SMAD2 expression. In the latter set of cells, cell lysates were collected in preparation for western blot analysis.

### ***Western blot***

Cultured cells were lysed with T-PER® Tissue Protein Extraction Reagent with the addition of protease inhibitors (Pierce, Rockford, IL). Equal amounts of cellular protein were loaded into each well and separated by 10% sodium dodecyl sulfate-polyacrylamide gel electrophoresis (SDS-PAGE). Nitrocellulose membrane blotting was then performed under standard conditions. For immunoblotting, we used the following primary antibodies: mouse anti- $\beta$ -actin IgG (1:8,000) (Sigma), rabbit anti-TGF- $\beta$ 1 IgG (1:1000) (Abcam Inc.), goat anti-Myf-5 (Santa Cruz

Biotechnology, Inc.), mouse anti-MyoD and myogenin IgGs (1:250) (BD Biosciences), goat anti-SMAD2 and p-SMAD2 IgGs (Cell signaling Technology, Danvers, MA).

### ***Real time PCR***

C2C12 cells were grown in media containing varying amounts of follistatin at 0, 200, 400 and 1000 ng/ml that was added every 48 hours and collected at 1 and 4 days after plating using Trizol (Invitrogen). RNA was precipitated, processed and purified using the Qiagen RNeasy kit. RNA was DNase treated, and quantitated on a spectrophotometer. To normalize variation between samples a standard amount of 10ng of RNA was used. Promega Go-Taq 2-step RT-qPCR (A6010) was used to run all samples. Predesigned SYBR primer sets were obtained from Qiagen for both myostatin and GAPDH. ABI 7900HT fast real time PCR system was used to obtain cycle threshold (Ct) values of the genes of interest. Ct values were calculated using ABI SDS 2.3 software. Samples were normalized to GAPDH expression, and the  $\Delta\Delta C_t$  method of data analysis was used. The formula for fold change is  $2^{-(\Delta\Delta C_t)}$  and is used to show differences between treatments. Gene expression levels were examined and normalized to untreated control cultures.

### ***Statistics***

All data are reported as the mean  $\pm$  standard deviation (SD) or mean  $\pm$  standard error of the mean (SEM), and data analyses have been performed with Student's t-test for comparisons between two groups as well as with a One-Way ANOVA for comparisons among three or more groups (SPSS Jandel Corporation). For all statistically significant differences observed after performing One-Way ANOVA, the appropriate multiple comparison tests were used to perform a post-hoc analysis. Statistical significance was considered for all P-values  $<0.05$ ; values marked with asterisks (\*) and (\*\*) represent  $P < 0.05$  and  $P < 0.01$ , respectively.

## Results

### *Improved healing in follistatin over-expressing skeletal muscle*

In order to investigate whether follistatin could promote skeletal muscle healing after injury, we used a follistatin over-expressing transgenic mouse model to examine whether skeletal muscle healing after injury would differ from WT controls. Following laceration, the gastrocnemius muscles (GMs) from WT and follistatin over-expressing (FLST/OE) mice were observed to undergo regeneration as confirmed by visualizing the presence of centro-nucleated myofibers (Fig. 1A). The myofiber diameters were determined 7 days after laceration and ranged in size from 5-35  $\mu\text{m}$ . (Fig. 1B). Over time, the diameters of the regenerating myofibers increased in size with the mean diameter of the regenerating myofibers in the follistatin over-expressing muscle being significantly larger than those observed in the WT muscle. The mean regenerating fiber diameters in the follistatin over-expressing mice, as measured at the post-laceration time points of 7, 14, 30 days, and 1.5 years, were larger by approximately 25.3% ( $19.37 \pm 0.80 \mu\text{m}$  vs.  $15.46 \pm 0.81 \mu\text{m}$ ;  $P < 0.01^{**}$ ), 31.6% ( $39.77 \pm 3.69 \mu\text{m}$  vs.  $30.22 \pm 2.75 \mu\text{m}$ ;  $P < 0.01^{**}$ ), 32.5% ( $45.55 \pm 3.03 \mu\text{m}$  vs.  $34.38 \pm 1.56 \mu\text{m}$ ;  $P < 0.01^{**}$ ), and 36.3% ( $64.36 \pm 5.40 \mu\text{m}$  vs.  $47.22 \pm 3.49 \mu\text{m}$ ;  $P < 0.01^{**}$ ) respectively, than those of the WT mice (Fig. 1C). The absolute differences in the mean diameters of the regenerating myofibers between the WT and follistatin over-expressing mice were also shown to increase (green curve Fig. 1C). Accordingly, the injured muscles of follistatin over-expressing mice compared to the WT animals contained a higher percentage of larger myofibers at each of the post-injury time points tested. For example, at 7 days 51% of the regenerating WT myofibers were larger than 15  $\mu\text{m}$ , whereas, 86% of the regenerating follistatin over-expressing myofibers were larger than 15  $\mu\text{m}$ ; at 14 days, 45% of the regenerating myofibers of the WT mice were larger than 30  $\mu\text{m}$  while 73% of the regenerating myofibers of the follistatin over-expressing mice fell into the 30 to 85  $\mu\text{m}$  diameter group ; at 30 days, 40% of the regenerating myofibers of WT mice were larger than 35  $\mu\text{m}$ , while 73% of the regenerating

follistatin over-expressing myofibers were larger than 35  $\mu\text{m}$  (Fig. 1B). Nevertheless, there was no significant difference in the percentage of regenerating myofibers between the injured follistatin over-expressing muscles and the WT control muscles (see Supplemental Figure S1 at <http://ajp.amjpathol.org>).

In addition to the differences in myofiber regeneration, we observed significant differences in the deposition of collagenous connective tissue after injury between the regenerating WT and follistatin over-expressing muscles. Specifically, at 14 days post-laceration, fibrosis developed extensively in the WT muscles, but was relatively limited in the follistatin over-expressing muscles (Fig. 2A). The amounts of fibrosis quantified at 14 days post-injury within the WT and follistatin over-expressing GMs, respectively, were  $8.71 \pm 2.36\%$  and  $3.54 \pm 1.71\%$  ( $P < 0.01^{**}$ ) (Fig. 2B). Compared to these values obtained at 14 days, our quantification analysis showed a reduction in fibrosis at 30 days in the injured WT and follistatin over-expressing GMs (Fig. 2A); in spite of this, the relative amounts of fibrosis formation in the WT GMs continued to be significantly greater than the follistatin over-expressing GMs ( $5.57 \pm 1.94\%$  vs.  $2.10 \pm 1.10\%$ ;  $P < 0.01^{**}$ ) (Fig. 2B). Fibrosis in both the injured GMs of the WT and follistatin over-expressing mice was reduced at 1.5 years after injury (data not shown).

It has been reported that follistatin inhibits myostatin by directly binding to the molecule<sup>34-35</sup>. Notably, we found a reduction of the myostatin protein in the injured muscles of follistatin over-expressing mice. This became apparent two weeks after injury when we noted that the follistatin over-expressing muscles showed less myostatin signal than the WT muscles, as indicated by immunostaining (Fig. 3A). Collagen IV (green) stains the basal lamina, which outlines the myofibers, and the myostatin protein (red) is seen to be mostly localized in the cytoplasm of the regenerating, centro-nucleated, fibers (Fig. 3A arrows); however, some of the myostatin-positive regenerating myofibers lacked a completely intact basal lamina (Fig. 3A arrowheads). When measuring the area and intensity of the myostatin signal in the injured muscles, we found that myostatin in the injured follistatin over-expressing muscles was

significantly lower than that observed in the WT controls (Fig. 3B). Similarly, two weeks after injury, the activin A signals in the injured follistatin over-expressing muscles were also decreased when compared to the WT controls by immunostaining (see Supplemental Figure S2 at <http://ajp.amjpathol.org>). Furthermore, we detected a trend that phosphorylation levels of SMAD2/3, in the injured muscles of follistatin over-expressing mice were lower than that observed in the WT controls (see Supplemental Figure S3 at <http://ajp.amjpathol.org>).

It has been found that follistatin stimulates angiogenesis both *in vitro* and *in vivo* <sup>44</sup> and that the presence of increased angiogenesis has been reported to be involved with a reduction in the formation of fibrosis <sup>45</sup>. These findings have led us to examine neovascularization in the injured follistatin over-expressing and WT muscles. We assessed the vascularity of injured follistatin over-expressing and WT muscles at 30 days following laceration, and observed that the follistatin over-expressing muscles had a significantly larger number of CD31-positive capillary-like structures along the zone of injury in comparison to their WT counterparts (Fig. 3C, D). This indicates that increased vascularity may be, at least partially, responsible for the improved muscle healing observed in follistatin over-expressing mice.

### ***Comparison of WT and Follistatin Over-expressing Muscle Progenitor Cells***

To elucidate why follistatin over-expressing muscles show a better regenerative capacity after injury than WT muscles, we compared MPCs isolated from follistatin over-expressing skeletal muscle to WT MPCs. We used flow cytometry and immunocytochemistry to analyze the expression of stem cell (Sca-1, CD34) and myogenic (desmin) markers, and also determined the proliferation and myogenic differentiation capacities of these two cell populations. The heterogeneous profile of the stem cell marker expression is apparent from the histograms in Fig. 4A. Cell populations from both the follistatin over-expressing and WT groups expressed these surface markers (Sca-1+ & CD34+, Sca-1+ only, and CD34+ only), though at different levels.



Compared to the WT MPC populations, the follistatin over-expressing populations contained a significantly larger percentage of cells that were positive for Sca-1 (Fig. 4A, B). The representative images of the flow cytometry dot plots showed that one of the follistatin over-expressing MPC populations and one of the WT MPC populations contained 46.5% and 24% Sca-1 positive cells, respectively (Fig. 4C). In the low serum medium, both follistatin over-expressing and WT MPCs were capable of fusing into multinucleated myotubes as demonstrated by MyHC and DAPI staining (Fig. 4D). The percentage of desmin-positive cells and proliferation and myogenic differentiation capacities were also compared between the follistatin over-expressing and WT MPC populations; however, due to high variability, no significant differences were observed (data not shown).

MPCs are a population of primary long-term proliferating cells that regenerate skeletal muscle more efficiently than myoblasts when transplanted into the muscles of dystrophic mice<sup>43, 46</sup>. We posited that follistatin over-expressing MPCs would likely be superior to WT MPCs at regenerating skeletal muscle due to our finding that injured follistatin over-expressing muscles underwent better muscle regeneration than did the WT control muscles. Using the preplate technique<sup>43, 46</sup>, we isolated MPCs from both WT and follistatin over-expressing mice and compared their ability to regenerate skeletal muscle by injecting them into the GMs of mdx/SCID mice. Quantification of the number of dystrophin-positive myofibers was performed to evaluate the cell transplantation efficiency. Notwithstanding, a high degree of variability was observed in the WT and follistatin over-expressing MPCs abilities to regenerate myofibers *in vivo* (Fig. 5A). Only 2 out of 5 of the WT MPC populations produced over 200 dystrophin-positive myofibers, while 6 out of 7 of the follistatin over-expressing cell populations regenerated more than 200 myofibers. Specifically, whereas the WT MPC population with the greatest potential to generate dystrophin-positive myofibers was able to regenerate 400 fibers, 4 of the 7 follistatin over-expressing populations regenerated between 500 and 1398 fibers (Fig. 5A). Moreover, all the follistatin over-expressing MPC populations produced more fibers than the mean fiber number

(e.g., 195.6 myofibers) produced by the WT MPC populations (Fig. 5A, B). Overall, the follistatin over-expressing MPCs (n = 7) produced significantly larger muscle engraftments than did the WT cells (n = 5) ( $592.8 \pm 154.9$  vs.  $195.6 \pm 65.4$ ; Mean  $\pm$  SEM;  $P = 0.023^*$ ; t-test) (Fig. 5B). Two representative dystrophin-positive engraftments derived from the follistatin over-expressing and WT MPCs (784 vs. 494 dystrophin-positive myofibers, respectively) are shown in Fig 5C.

### ***Interaction between Follistatin and TGF- $\beta$ Superfamily Members***

Recombinant myostatin protein inhibited the myogenic differentiation ability of C2C12 myoblasts *in vitro*, and our results indicate that follistatin can neutralize exogenous myostatin, thereby allowing the C2C12 myoblasts to undergo myogenic differentiation (Fig. 6A). We further showed that, much as is the case with myostatin's effect on myoblasts, activin A can also significantly inhibit the myogenic differentiation capacity of C2C12 cells (Fig. 6B). We also demonstrated that follistatin can significantly attenuate the myogenic inhibitory effect that activin A has on C2C12 myoblast's capacity to differentiate into myotubes (Fig. 6C).

Myogenic differentiation, in particular, involves sequential steps where myoblasts initially retract from the cell cycle and thereafter differentiate and fuse into multi-nucleated myotubes. TGF- $\beta$ 1 inhibits myoblast differentiation and although muscle cells are able to withdraw from the cell cycle when cultured in fusion induction medium supplemented with TGF- $\beta$  1, these cells fail to fuse into myotubes as is evidenced by the lack of muscle creatine kinase and nicotinic acetylcholine receptor expression<sup>47</sup>. Here we have shown that TGF- $\beta$ 1 inhibits the myogenic differentiation of C2C12 myoblasts in fusion induction medium. In contrast to the extensive myotube formation observed in the control C2C12 cells not treated with TGF- $\beta$ 1, there were only a few small myotubes interspersed among numerous nuclei (blue) in cell cultures treated with TGF- $\beta$ 1 (Fig. 7A). In cell cultures treated with both TGF- $\beta$ 1 and increasing concentrations of follistatin, follistatin was observed to counteract TGF- $\beta$ 1's inhibition of the

C2C12 myoblast's myogenic capacity (Fig. 7A). The fusion indices indicated that follistatin significantly increased the myogenic differentiation capacity of the C2C12 myoblasts and that TGF- $\beta$ 1 significantly decreased their myogenic differentiation capacity. Moreover, follistatin prevented TGF- $\beta$ 1 from inhibiting myogenesis and partially restored the myogenic differentiation capacity of the C2C12 myoblasts exposed to TGF- $\beta$ 1 (Fig. 7B). Follow-up experiments demonstrated that follistatin also decreased TGF- $\beta$ 1 expression by the C2C12 myoblasts with and without the exogenous application of TGF- $\beta$ 1 (Fig. 7C). Additionally, the TGF- $\beta$ 1 signaling pathway relies on the activation of an intracellular SMAD signaling cascade, and our results indicated that follistatin blocks this pathway by reducing the expression and phosphorylation of SMAD2 (Fig. 7D).

Our group has previously shown that follistatin stimulates C2C12 myoblasts to undergo myogenic differentiation<sup>23</sup> and significantly increases the fusion index of the cells when compared to untreated controls, and does so in a dose-dependent fashion<sup>23</sup>. In our complementary experiments from the current study, during the early stages of myogenic differentiation (day 1) -- when there is no detectable myotube formation -- there is a notable increase in the expressions of MyoD and Myf5 in the C2C12 cells treated with follistatin when compared to untreated cells. During the late stages of differentiation (day 4), in which the formation of myotubes is quite extensive, C2C12 cells exposed to follistatin augment their expression of myogenin and maintain elevated expression levels of Myf-5 compared to the untreated controls (Fig. 7E).

### **AAV2-delivered MPRO inhibits MSTN activity in vivo**

In order to make our results described above more therapeutically relevant, we performed an experiment to examine whether blocking MSTN using an AAV2-MPRO vector could improve the healing of injured skeletal muscle. Either an AAV2-MPRO or AAV2-GFP control vector was injected into the GMs of adult C57BL/6J mice 1 month prior to injuring the muscles. This delay

enabled the transgenes a sufficient amount of time to begin potently expressing in the injected muscles. The mice were then sacrificed 4 weeks after GM laceration injury. Similar to what we observed in the follistatin over-expressing muscles, the injured GMs over-expressing MPRO exhibited better healing than the AAV2-GFP transduced controls. Masson's Trichrome staining showed extensive fibrosis infiltration in the injured WT skeletal muscle, while the injured AAV2-MPRO transduced muscle formed significantly less fibrotic tissue (Fig. 8A, B, ( $7.2 \pm 1.1\%$  vs.  $2.6 \pm 1.0\%$ ; mean  $\pm$  SD,  $P < 0.01^{**}$ )). The expression of the MPRO gene in the transduced muscles indicates that genes delivered by the AAV2 vector were stably expressed by the muscle (Fig. 8C). The weights of the AAV2-MPRO transduced GMs were also significantly higher than their WT counterparts (Fig. 8D). Moreover, we observed larger regenerating myofibers in the AAV2-MPRO transduced injured muscles than in the injured WT muscles (Fig. 8E). The mean diameter of the regenerating myofibers in the GMs over-expressing MPRO was significantly increased (by 26.7%) over what was observed in the non-transduced GMs ( $36.8 \pm 3.8 \mu\text{m}$  vs.  $29.0 \pm 2.2 \mu\text{m}$ ; mean  $\pm$  SD,  $P < 0.01^{**}$ ) (Fig. 8F). Correspondingly, the distribution of diameters of the regenerating myofibers revealed that 78.0% of the regenerating myofibers in the control muscles had diameters smaller than  $35 \mu\text{m}$  when compared to 46.3% found in the AAV2-MPRO transduced muscles. In contrast, 53.7% of the regenerating myofibers in the injured AAV2-MPRO transduced muscles had a diameter in the range of  $35$  to  $70 \mu\text{m}$  (Fig. 8G).

## **Discussion**

In this study, we showed that the skeletal muscle healing of follistatin over-expressing mice is accelerated when compared to the skeletal muscle of WT mice. Specifically, the mean diameter of the regenerating myofibers in the injured follistatin over-expressing muscles remained significantly larger than their WT counterparts. Moreover, fibrosis formation was significantly lower in the injured follistatin over-expressing muscles than the injured WT muscles. These

results are comparable to those that we previously observed in the injured GMs of myostatin knockout mice <sup>23</sup>. There are several possible explanations for follistatin's augmentation which include: a) decreasing levels of myostatin, activin A, and the phosphorylated SMAD2/3, b) promoting vascularity in the injured muscles, and c) enhancing the ability of MPCs to regenerate the injured muscle fibers. This last explanation was confirmed by *in vitro* results which showed that follistatin could promote myoblast differentiation by blocking myostatin, activin A, and TGF- $\beta$ 1, all negative regulators of muscle regeneration, and also by augmenting the expression of the myogenic transcription factors MyoD, Myf5 and Myogenin. Although we will discuss these events individually, we highlight that they are not mutually exclusive of one another, but rather, illustrate how follistatin can synergistically promote healing through each of these processes.

### ***Mechanisms Involved in the Reduction of Fibrosis Formation in Injured Follistatin Over-expressing Muscle***

TGF- $\beta$ 1 expression in injured skeletal muscle is time dependent, peaking between 3-5 days and then again at 10-14 days post-injury <sup>5-6, 48</sup>. The latter event appears to be associated with the formation of fibrosis and ineffective muscle regeneration <sup>5</sup>. When the second peak of TGF- $\beta$ 1 expression is blocked with the administration of an antifibrotic agent at 14 days post-injury, it leads to histological and physiological improvements of the injured muscles <sup>5, 10-14, 16-17</sup>. Coincidentally, our *in vivo* studies showed significant decreases in myostatin immunostaining among injured follistatin over-expressing GMs 14 days after injury. Given our *in vitro* results that follistatin doesn't down-regulate mRNA expression of myostatin in C2C12 myoblasts (see Supplemental Figure S4 at <http://ajp.amjpathol.org>), the decreased myostatin observed in injured follistatin over-expressing muscle may not result from a decrease in myostatin transcription. It has been shown that follistatin can be released into the blood circulation <sup>26, 37</sup>; therefore, the reduction in the myostatin signal in the injured follistatin over-expressing muscle could be partially due to the fact that excessive circulating follistatin and follistatin within the



muscle's extracellular matrix, can sequester myostatin and prevent it from binding to the injured muscle tissue. Moreover, some small regenerating myofibers, without intact basal lamina, were found in the current study to be strongly myostatin positive in the injured WT and follistatin over-expressing GMs, which was similar to our previous findings<sup>23</sup>. Li et al reported that some regenerating myofibers appeared to degrade and transform into myofibroblasts which aggravated fibrosis formation in the injured skeletal muscles<sup>5</sup>. If this is the case, these myostatin positive, basal lamina deficient regenerating fibers may represent a transitional state of regenerating myofibers that are undergoing the differentiation process into myofibroblasts. A decrease in the amount of myostatin at the injury site likely accounts for the reduction in fibrosis observed in the injured follistatin over-expressing muscles, given the fact that myostatin directly stimulates fibrosis in skeletal muscle<sup>20,23,27</sup> and the lack of myostatin would also attenuate the pro-fibrotic effects of TGF- $\beta$ 1<sup>23</sup>. Additionally, we showed that follistatin down-regulates the expression of TGF- $\beta$ 1 and counteracts its activity *in vitro*. Myostatin, TGF- $\beta$ 1, and activin A all belong to the TGF- $\beta$  superfamily and all signal through the TGF- $\beta$ /SMAD2/3 signaling pathway. Our data indicates that there is an overall decrease in the phosphorylation level of SMAD2/3 in the injured follistatin over-expressing muscle when compared to the WT controls. Although we do not have direct evidence showing that follistatin also reduces fibrosis through the inhibition of TGF- $\beta$ 1 and activin A, our results appear to demonstrate that follistatin decreases the TGF- $\beta$ -like signaling that occurs through the SMAD2/3 pathway, thereby attenuating the inhibitory effect of this pathway on skeletal muscle healing.

We also showed that there are significantly more CD31 positive capillary-like structures that appeared in the injured follistatin over-expressing muscles than in the injured WT controls; however, more evidence is required to validate the vascular functionality of these CD31-positive structures. It is noteworthy to point out that angiogenesis correlates with an increase in skeletal and cardiac muscle regeneration and a reduction in fibrosis<sup>45,49-52</sup>. In the present study there is insufficient evidence to indicate whether follistatin directly stimulates angiogenesis in injured

skeletal muscle; nevertheless, accumulating evidence in other studies suggest that follistatin expression can be positively correlated with angiogenesis by a variety of different cells and tissues <sup>42,53-55</sup>. Follistatin expression is up-regulated by activated endothelial cells, but down-regulated upon the cell's withdrawal from the cell cycle <sup>55</sup>. Follistatin promotes the proliferation of several types of endothelial cells including human umbilical vein endothelial cells and bovine aortic endothelial cells <sup>55</sup>. Follistatin alone moderately stimulates angiogenesis in the rabbit cornea and its angiogenic effect can be greatly reinforced when combined with basic fibroblast growth factor <sup>55</sup>. Additionally, follistatin was recently found to function as a binding protein of angiogenin, which is known to induce angiogenesis via the activation of endothelial and smooth muscle cells <sup>53</sup>. Follistatin and angiogenin co-localize in the nuclei of HeLa cells, suggesting that the follistatin and angiogenin interaction may play an important role in angiogenin-induced angiogenesis <sup>53</sup>. A "loss of function" experiment validated that the follistatin isoform 288 is essential for promoting angiogenesis during mouse embryo formation <sup>56</sup>. Importantly, activin A and TGF- $\beta$ 1 have been shown to inhibit the growth and activation of a spectrum of vascular endothelial cells <sup>55,57</sup>; therefore, it is possible that follistatin partially promotes angiogenesis by antagonizing TGF- $\beta$ s' inhibition of endothelial cells. Nevertheless, the effects that follistatin and TGF- $\beta$ s have on skeletal muscle vascular endothelial cells remain to be elucidated. Revascularization in injured skeletal muscle is a critical event during muscle regeneration. The speed and quality of tissue repair is directly correlated with the degree of vascular ingrowth into the muscle injury site, which provides an adequate supply of oxygen and nutrients to promote efficient regeneration <sup>58, 59</sup>. The regeneration of multinucleated myofibers in injured muscles will be impaired if there is an insufficient supply of oxygen due to an inadequate supply of energy resulting from insufficient aerobic metabolism <sup>58,60</sup>. Given the stimulatory effects that follistatin exerts on endothelial cells, it is reasonable to speculate that follistatin may be able to promote the growth of new capillaries in order to increase the blood supply to the injury site. The increase in

blood supply would further accelerate the resorption of scar tissue and increase muscle regeneration.

### ***Cellular Mechanism by which Follistatin Promotes Skeletal Muscle Regeneration after Injury.***

The development of skeletal muscle during embryogenesis and its regeneration after trauma, or in the setting of skeletal muscle disease, largely occurs through the differentiation of muscle cells into myofibers<sup>61-63</sup>. Satellite cells in adult skeletal muscle can be found within a niche between the basal lamina and sarcolemma of the myofibers, forming a pool of quiescent myogenic progenitor cells<sup>64</sup>. In response to muscle trauma and during disease processes, these cells are activated to re-enter the cell cycle, migrate from the basal lamina to the zone of injury, and undergo asymmetric divisions. A preponderance of daughter cells are committed to differentiate and fuse into multinucleated myofibers, while a small portion of self-renewing cells replenish the reservoir of satellite cells by re-entering a quiescent state.

Myostatin inhibits satellite cell self-renewal by down-regulating their G1 to S progression within the cell cycle retaining the satellite cells in a quiescent state<sup>65-66</sup>. Inversely, myostatin knockout skeletal muscle possesses more satellite cells than their WT counterparts, likely resulting from an increase in proliferation and a delay in myogenic differentiation by the adult myostatin knockout satellite cells<sup>65</sup>. Based on this information, we sought to determine the impact that follistatin would have on the regenerative capacity of MPCs. MPCs are a heterogeneous population consisting of myoblasts, satellite cells, and stem cells. We injected MPCs isolated from both follistatin over-expressing and WT skeletal muscle of mice into the GMs of mdx/SCID mice to determine their regeneration efficiency. We found that overall, the follistatin over-expressing MPC populations regenerated a greater numbers of dystrophin-positive myofibers when compared to the WT MPCs; however, it should be noted that not all the follistatin over-expressing MPC populations outperformed their WT counterparts. Variations in

regard to the regenerative capacity of both cell types was readily apparent and is a common phenomenon observed collectively when myoblasts, satellite cells, or muscle stem cells are transplanted intramuscularly <sup>43, 46, 67</sup>. Specifically, dystrophin-positive myofibers regenerated by the follistatin over-expressing MPC populations varied from 200 to 1398 fibers, while those produced by the WT MPC populations varied from 27 to 400 fibers. The increase in the regenerative capacity of the follistatin over-expressing MPC populations probably partially accounts for the better regeneration observed in the injured follistatin over-expressing muscles than was seen in the WT muscles. These findings may help researchers to genetically engineer an optimal cell population for cell-based therapies to treat DMD, a lethal sex-linked recessive muscle-wasting disease which stems from a variety of different mutations of the dystrophin gene <sup>68-69</sup>. For instance, the transplantation of muscle cells carrying a follistatin transgene into the dystrophic muscle of a DMD patient may enhance the success of cell transplantation in comparison to that of un-engineered muscle progenitor cells <sup>70</sup>.

We also investigated whether the cell surface marker profile, proliferation rate, and myogenic differentiation capacity of the MPCs could highlight the mechanism by which these cells display a higher muscle regenerative potential *in vivo*; however, we found that the MPC populations isolated from both types of mice exhibited a broad heterogeneity of cell surface markers, proliferation rates, and myogenic capacities *in vitro*. In spite of this heterogeneity, the follistatin over-expressing MPC populations contained a significantly larger percentage of Sca-1+ cells than the WT controls. It has been reported that among male muscle-derived stem cell populations, a higher percentage of Sca-1+ cells in the cell population appeared to positively correlate with a higher regenerative capacity when transplanted into dystrophic mdx mouse skeletal muscle; however, this is not the case for female muscle-derived stem cells <sup>67</sup>. These findings are consistent with our current findings, in that all the cells for these studies were isolated from male mice and the follistatin over-expressing MPC populations utilized in the

current study had a higher percentage of Sca-1+ cells and showed a better regenerative capacity than the WT cells.

## ***Molecular Mechanisms by which Follistatin Promotes Myogenesis***

### *Interaction between follistatin and TGF $\beta$ s*

The over-expression of follistatin probably has a more profound effect on muscle growth than solely blocking myostatin. As stated above, we found that the differentiation of myoblasts *in vitro* is inhibited by myostatin, activin A, and TGF- $\beta$ 1. Each of these factors appears to be inhibited by follistatin; as a result, myoblast differentiation capacity can be restored. While it is already known that follistatin directly antagonizes both myostatin and activin A, further investigation is required to determine whether follistatin inhibits TGF- $\beta$ 1 directly or indirectly. Moreover, evidence is emerging that activin A may be one of the key growth factors that function in tandem with myostatin to limit muscle growth <sup>41, 71</sup>. The follistatin-I mutant, that does not bind activin A effectively, promotes muscle growth to a lesser extent than WT follistatin. Furthermore, unlike WT follistatin, the mutant follistatin fails to induce an increase in the muscle mass of myostatin knockout mice <sup>71</sup>. It has been recently reported that activin A knockout mice exhibit significant size increases in both their pectoralis and tricep muscles, which provides genetic evidence that activin A may be one of the key growth factors that function in tandem with myostatin to limit muscle growth <sup>41</sup>. In this study, our results have shown that that follistatin inhibits not only myostatin, but also activin A and TGF- $\beta$ 1 in C2C12 myoblast, which may partially explain why follistatin exerts a more striking effect in promoting muscle regeneration in both injured and dystrophic muscle.

There is some evidence from previously published reports that also indicate that follistatin's effect on muscle growth may not be exclusively linked to blocking the effects of myostatin including: 1) Follistatin over-expressing mice display even greater skeletal muscle mass than do myostatin knockout mice, which suggests that follistatin's effect on the skeletal



muscles may result from the ablation of other negative regulators of muscle growth besides myostatin<sup>35</sup>. 2) Lee et al. have also reported that the effect of follistatin on skeletal muscle does not result solely from the inhibition of myostatin activity. Their findings demonstrated that the over-expression of follistatin led to further increases in the muscle mass of myostatin knockout mice when compared to myostatin knockout mice controls alone<sup>72</sup>. 3) Blocking the activin type IIB receptor causes further increases in the skeletal muscle mass of myostatin knockout mice, suggesting that other growth factors can limit muscle growth via the activin type IIB receptor as does myostatin<sup>40</sup>. The above results implicate the existence of other molecules that could be involved in the observed beneficial effects of follistatin on muscle growth.

*Skeletal muscle injury comparisons between myostatin knockout and follistatin over-expressing mice*

We have previously examined how the loss of myostatin benefits injured skeletal muscle using the same laceration injury model as in the current study<sup>23</sup>. When retrospectively comparing the current results to those collected from the myostatin knockout mice, we found that the mean diameter of the regenerating myofibers in the follistatin over-expressing mice was 32.50% greater than the WT mice 4 weeks post-injury compared to a 21.22% increase over the WT controls seen in the myostatin knockout mice. Interestingly, there is not much difference in the formation of fibrosis between injured follistatin over-expressing and myostatin knockout muscle. Although injured follistatin over-expressing muscle shows more dramatic reductions in fibrosis formation than injured myostatin knockout muscle (59.36% vs. 25.00%) 2 weeks after laceration; however, by the end of 4 weeks post-injury, these reductions in fibrosis were inconsequential between the two groups (66.70% vs. 62.30%) (see Supplemental Table S1 at <http://ajp.amjpathol.org>). Similar reductions in fibrosis in injured myostatin knockout and follistatin over-expressing muscle suggest that the inhibition of myostatin may largely account for the decrease observed in fibrosis in the injured follistatin over-expressing muscles.

Myostatin knockout MPCs can regenerate significantly more myofibers than WT control MPCs when intramuscularly transplanted into mdx/SCID mice <sup>23</sup>. When follistatin over-expressing, WT and myostatin knockout progenitor cells were injected in parallel into the skeletal muscle of mdx/SCID mice, the follistatin over-expressing MPCs regenerated three times as many dystrophin-positive myofibers as the WT MPCs ( $592.8 \pm 154.9$  vs.  $195.6 \pm 65.4$ ), whereas the myostatin knockout MPCs showed about a 1.5 fold increase over the WT MPCs ( $518.1 \pm 117.6$  vs.  $195.6 \pm 65.4$ ) (Fig. 5A, B, and see Supplemental Figure S5 and Table S1 at <http://ajp.amjpathol.org>). Four out of seven (57%) of the follistatin over-expressing MPC populations regenerated more than 500 fibers; in contrast, only 2 out of 5 (40%) of the myostatin knockout- muscle progenitor cell populations did so (Fig. 5A, and see Supplemental Figure S5 at <http://ajp.amjpathol.org>).

Apart from the results collected from the myostatin knockout and follistatin over-expressing mice, we further demonstrated that AAV2-mediated MPRO gene therapy improved muscle healing in WT skeletal muscle by inhibiting myostatin. This suggests that inhibiting myostatin is applicable for the treatment of injured muscles and myopathic disorders. Taken together, follistatin-based therapies may represent a more effective therapeutic strategy over others that only antagonize myostatin. Moreover, since follistatin generally promotes muscle hypertrophy without targeting specific defective genes (e.g., dystrophin, DMD), follistatin renders itself as a potential universal therapeutic reagent to treat a board spectrum of muscle diseases, especially the muscular dystrophies, which lack a clear pathogenic gene defect such as facioscapulohumeral muscular dystrophy. Furthermore, follistatin exhibited no unusual side-effects on the reproductive capacity of mice <sup>37</sup>. Although additional studies are required on primates to warrant follistatin's feasibility for clinical translation, its use stands to be potentially beneficial for the treatment of a variety of skeletal muscle injuries and disorders.

## References

1. Border WA, Noble NA: Transforming growth factor beta in tissue fibrosis, *N Engl J Med* 1994, 331:1286-1292
2. Lijnen PJ, Petrov VV, Fagard RH: Induction of cardiac fibrosis by transforming growth factor-beta(1), *Mol Genet Metab* 2000, 71:418-435
3. Waltenberger J, Lundin L, Oberg K, Wilander E, Miyazono K, Heldin CH, Funa K: Involvement of transforming growth factor-beta in the formation of fibrotic lesions in carcinoid heart disease, *Am J Pathol* 1993, 142:71-78
4. Yamamoto T, Noble NA, Miller DE, Border WA: Sustained expression of TGF-beta 1 underlies development of progressive kidney fibrosis, *Kidney Int* 1994, 45:916-927
5. Li Y, Foster W, Deasy BM, Chan Y, Prisk V, Tang Y, Cummins J, Huard J: Transforming growth factor-beta1 induces the differentiation of myogenic cells into fibrotic cells in injured skeletal muscle: a key event in muscle fibrogenesis, *Am J Pathol* 2004, 164:1007-1019
6. Li Y, Huard J: Differentiation of muscle-derived cells into myofibroblasts in injured skeletal muscle, *Am J Pathol* 2002, 161:895-907
7. Bernasconi P, Torchiana E, Confalonieri P, Brugnoli R, Barresi R, Mora M, Cornelio F, Morandi L, Mantegazza R: Expression of transforming growth factor-beta 1 in dystrophic patient muscles correlates with fibrosis. Pathogenetic role of a fibrogenic cytokine, *J Clin Invest* 1995, 96:1137-1144
8. Gosselin LE, Williams JE, Deering M, Brazeau D, Koury S, Martinez DA: Localization and early time course of TGF-beta 1 mRNA expression in dystrophic muscle, *Muscle Nerve* 2004, 30:645-653
9. Cohn RD, van Erp C, Habashi JP, Soleimani AA, Klein EC, Lisi MT, Gamradt M, ap Rhys CM, Holm TM, Loeys BL, Ramirez F, Judge DP, Ward CW, Dietz HC: Angiotensin II type 1 receptor blockade attenuates TGF-beta-induced failure of muscle regeneration in multiple myopathic states, *Nat Med* 2007, 13:204-210
10. Chan YS, Li Y, Foster W, Fu FH, Huard J: The use of suramin, an antifibrotic agent, to improve muscle recovery after strain injury, *Am J Sports Med* 2005, 33:43-51
11. Chan YS, Li Y, Foster W, Horaguchi T, Somogyi G, Fu FH, Huard J: Antifibrotic effects of suramin in injured skeletal muscle after laceration, *J Appl Physiol* 2003, 95:771-780
12. Foster W, Li Y, Usas A, Somogyi G, Huard J: Gamma interferon as an antifibrosis agent in skeletal muscle, *J Orthop Res* 2003, 21:798-804
13. Sato K, Li Y, Foster W, Fukushima K, Badlani N, Adachi N, Usas A, Fu FH, Huard J: Improvement of muscle healing through enhancement of muscle regeneration and prevention of fibrosis, *Muscle Nerve* 2003, 28:365-372
14. Fukushima K, Badlani N, Usas A, Riano F, Fu F, Huard J: The use of an antifibrosis agent to improve muscle recovery after laceration, *Am J Sports Med* 2001, 29:394-402
15. Yamazaki M, Minota S, Sakurai H, Miyazono K, Yamada A, Kanazawa I, Kawai M: Expression of transforming growth factor-beta 1 and its relation to endomysial fibrosis in progressive muscular dystrophy, *Am J Pathol* 1994, 144:221-226
16. Li Y, Negishi S, Sakamoto M, Usas A, Huard J: The use of relaxin improves healing in injured muscle, *Ann N Y Acad Sci* 2005, 1041:395-397

17. Negishi S, Li Y, Usas A, Fu FH, Huard J: The effect of relaxin treatment on skeletal muscle injuries, *Am J Sports Med* 2005, 33:1816-1824
18. Bedair HS, Karthikeyan T, Quintero A, Li Y, Huard J: Angiotensin II receptor blockade administered after injury improves muscle regeneration and decreases fibrosis in normal skeletal muscle, *Am J Sports Med* 2008, 36:1548-1554
19. Bogdanovich S, Krag TO, Barton ER, Morris LD, Whittemore LA, Ahima RS, Khurana TS: Functional improvement of dystrophic muscle by myostatin blockade, *Nature* 2002, 420:418-421
20. McCroskery S, Thomas M, Platt L, Hennebry A, Nishimura T, McLeay L, Sharma M, Kambadur R: Improved muscle healing through enhanced regeneration and reduced fibrosis in myostatin-null mice, *J Cell Sci* 2005, 118:3531-3541
21. Qiao C, Li J, Jiang J, Zhu X, Wang B, Xiao X: Myostatin propeptide gene delivery by adeno-associated virus serotype 8 vectors enhances muscle growth and ameliorates dystrophic phenotypes in mdx mice, *Hum Gene Ther* 2008, 19:241-254
22. Wagner KR, McPherron AC, Winik N, Lee SJ: Loss of myostatin attenuates severity of muscular dystrophy in mdx mice, *Ann Neurol* 2002, 52:832-836
23. Zhu J, Li Y, Shen W, Qiao C, Ambrosio F, Lavasani M, Nozaki M, Branca MF, Huard J: Relationships between transforming growth factor-beta1, myostatin, and decorin: implications for skeletal muscle fibrosis, *J Biol Chem* 2007, 282:25852-25863
24. Parsons SA, Millay DP, Sargent MA, McNally EM, Molkentin JD: Age-dependent effect of myostatin blockade on disease severity in a murine model of limb-girdle muscular dystrophy, *Am J Pathol* 2006, 168:1975-1985
25. McPherron AC, Lawler AM, Lee SJ: Regulation of skeletal muscle mass in mice by a new TGF-beta superfamily member, *Nature* 1997, 387:83-90
26. Zimmers TA, Davies MV, Koniaris LG, Haynes P, Esquela AF, Tomkinson KN, McPherron AC, Wolfman NM, Lee SJ: Induction of cachexia in mice by systemically administered myostatin, *Science* 2002, 296:1486-1488
27. Li ZB, Kollias HD, Wagner KR: Myostatin directly regulates skeletal muscle fibrosis, *J Biol Chem* 2008,
28. Budasz-Rwiderska M, Jank M, Motyl T: Transforming growth factor-beta1 upregulates myostatin expression in mouse C2C12 myoblasts, *J Physiol Pharmacol* 2005, 56 Suppl 3:195-214
29. Miller TM, Kim SH, Yamanaka K, Hester M, Umapathi P, Arnson H, Rizo L, Mendell JR, Gage FH, Cleveland DW, Kaspar BK: Gene transfer demonstrates that muscle is not a primary target for non-cell-autonomous toxicity in familial amyotrophic lateral sclerosis, *Proc Natl Acad Sci U S A* 2006, 103:19546-19551
30. Wagner KR, Fleckenstein JL, Amato AA, Barohn RJ, Bushby K, Escolar DM, Flanigan KM, Pestronk A, Tawil R, Wolfe GI, Eagle M, Florence JM, King WM, Pandya S, Straub V, Juneau P, Meyers K, Csimma C, Araujo T, Allen R, Parsons SA, Wozney JM, Lavallie ER, Mendell JR: A phase I/II trial of MYO-029 in adult subjects with muscular dystrophy, *Ann Neurol* 2008, 63:561-571
31. Fainsod A, Deissler K, Yelin R, Marom K, Epstein M, Pillemer G, Steinbeisser H, Blum M: The dorsalizing and neural inducing gene follistatin is an antagonist of BMP-4, *Mech Dev* 1997, 63:39-50

32. Gamer LW, Wolfman NM, Celeste AJ, Hattersley G, Hewick R, Rosen V: A novel BMP expressed in developing mouse limb, spinal cord, and tail bud is a potent mesoderm inducer in *Xenopus* embryos, *Dev Biol* 1999, 208:222-232
33. Thompson TB, Lerch TF, Cook RW, Woodruff TK, Jandetzky TS: The structure of the follistatin:activin complex reveals antagonism of both type I and type II receptor binding, *Dev Cell* 2005, 9:535-543
34. Amthor H, Nicholas G, McKinnell I, Kemp CF, Sharma M, Kambadur R, Patel K: Follistatin complexes Myostatin and antagonises Myostatin-mediated inhibition of myogenesis, *Dev Biol* 2004, 270:19-30
35. Lee SJ, McPherron AC: Regulation of myostatin activity and muscle growth, *Proc Natl Acad Sci U S A* 2001, 98:9306-9311
36. Nakatani M, Takehara Y, Sugino H, Matsumoto M, Hashimoto O, Hasegawa Y, Murakami T, Uezumi A, Takeda S, Noji S, Sunada Y, Tsuchida K: Transgenic expression of a myostatin inhibitor derived from follistatin increases skeletal muscle mass and ameliorates dystrophic pathology in mdx mice, *Faseb J* 2008, 22:477-487
37. Haidet AM, Rizo L, Handy C, Umapathi P, Eagle A, Shilling C, Boue D, Martin PT, Sahenk Z, Mendell JR, Kaspar BK: Long-term enhancement of skeletal muscle mass and strength by single gene administration of myostatin inhibitors, *Proc Natl Acad Sci U S A* 2008, 105:4318-4322
38. Benabdallah BF, Bouchentouf M, Rousseau J, Tremblay JP: Overexpression of follistatin in human myoblasts increases their proliferation and differentiation, and improves the graft success in SCID mice, *Cell Transplant* 2009, 18:709-718
39. Kota J, Handy CR, Haidet AM, Montgomery CL, Eagle A, Rodino-Klapac LR, Tucker D, Shilling CJ, Therlfall WR, Walker CM, Weisbrode SE, Janssen PM, Clark KR, Sahenk Z, Mendell JR, Kaspar BK: Follistatin gene delivery enhances muscle growth and strength in nonhuman primates, *Sci Transl Med* 2009, 1:6ra15
40. Lee SJ, Reed LA, Davies MV, Girgenrath S, Goad ME, Tomkinson KN, Wright JF, Barker C, Ehrmantraut G, Holmstrom J, Trowell B, Gertz B, Jiang MS, Sebald SM, Matzuk M, Li E, Liang LF, Quattlebaum E, Stotish RL, Wolfman NM: Regulation of muscle growth by multiple ligands signaling through activin type II receptors, *Proc Natl Acad Sci U S A* 2005, 102:18117-18122
41. Lee SJ, Lee YS, Zimmers TA, Soleimani A, Matzuk MM, Tsuchida K, Cohn RD, Barton ER: Regulation of muscle mass by follistatin and activins, *Mol Endocrinol* 2010, 24:1998-2008
42. Jankowski RJ, Haluszczak C, Trucco M, Huard J: Flow cytometric characterization of myogenic cell populations obtained via the preplate technique: potential for rapid isolation of muscle-derived stem cells, *Hum Gene Ther* 2001, 12:619-628
43. Qu-Petersen Z, Deasy B, Jankowski R, Ikezawa M, Cummins J, Pruchnic R, Mytinger J, Cao B, Gates C, Wernig A, Huard J: Identification of a novel population of muscle stem cells in mice: potential for muscle regeneration, *J Cell Biol* 2002, 157:851-864
44. Krneta J, Kroll J, Alves F, Prahst C, Sananbenesi F, Dullin C, Kimmina S, Phillips DJ, Augustin HG: Dissociation of angiogenesis and tumorigenesis in follistatin- and activin-expressing tumors, *Cancer Res* 2006, 66:5686-5695



45. Nguyen F, Guigand L, Goubault-Leroux I, Wyers M, Cherel Y: Microvessel density in muscles of dogs with golden retriever muscular dystrophy, *Neuromuscul Disord* 2005, 15:154-163
46. Deasy BM, Gharaibeh BM, Pollett JB, Jones MM, Lucas MA, Kanda Y, Huard J: Long-term self-renewal of postnatal muscle-derived stem cells, *Mol Biol Cell* 2005, 16:3323-3333
47. Olson EN, Sternberg E, Hu JS, Spizz G, Wilcox C: Regulation of myogenic differentiation by type beta transforming growth factor, *J Cell Biol* 1986, 103:1799-1805
48. Shen W, Li Y, Tang Y, Cummins J, Huard J: NS-398, a cyclooxygenase-2-specific inhibitor, delays skeletal muscle healing by decreasing regeneration and promoting fibrosis, *Am J Pathol* 2005, 167:1105-1117
49. Ahn A, Frishman WH, Gutwein A, Passeri J, Nelson M: Therapeutic angiogenesis: a new treatment approach for ischemic heart disease--part I, *Cardiol Rev* 2008, 16:163-171
50. Okada M, Payne TR, Zheng B, Oshima H, Momoi N, Tobita K, Keller BB, Phillippi JA, Peault B, Huard J: Myogenic endothelial cells purified from human skeletal muscle improve cardiac function after transplantation into infarcted myocardium, *J Am Coll Cardiol* 2008, 52:1869-1880
51. Payne TR, Oshima H, Okada M, Momoi N, Tobita K, Keller BB, Peng H, Huard J: A relationship between vascular endothelial growth factor, angiogenesis, and cardiac repair after muscle stem cell transplantation into ischemic hearts, *J Am Coll Cardiol* 2007, 50:1677-1684
52. Deasy BM, Feduska JM, Payne TR, Li Y, Ambrosio F, Huard J: Effect of VEGF on the regenerative capacity of muscle stem cells in dystrophic skeletal muscle, *Mol Ther* 2009, 17:1788-1798
53. Gao X, Hu H, Zhu J, Xu Z: Identification and characterization of follistatin as a novel angiogenin-binding protein, *FEBS Lett* 2007, 581:5505-5510
54. Glienke J, Schmitt AO, Pilarsky C, Hinzmänn B, Weiss B, Rosenthal A, Thierauch KH: Differential gene expression by endothelial cells in distinct angiogenic states, *Eur J Biochem* 2000, 267:2820-2830
55. Kozian DH, Ziche M, Augustin HG: The activin-binding protein follistatin regulates autocrine endothelial cell activity and induces angiogenesis, *Lab Invest* 1997, 76:267-276
56. Lin SY, Craythorn RG, O'Connor AE, Matzuk MM, Girling JE, Morrison JR, de Kretser DM: Female infertility and disrupted angiogenesis are actions of specific follistatin isoforms, *Mol Endocrinol* 2008, 22:415-429
57. McCarthy SA, Bicknell R: Inhibition of vascular endothelial cell growth by activin-A, *J Biol Chem* 1993, 268:23066-23071
58. Jarvinen M: Healing of a crush injury in rat striated muscle. 3. A micro-angiographical study of the effect of early mobilization and immobilization on capillary ingrowth, *Acta Pathol Microbiol Scand A* 1976, 84:85-94
59. Jozsa L, Reffy A, Demel S, Szilagyi I: Alterations of oxygen and carbon dioxide tensions in crush-injured calf muscles of rat, *Z Exp Chir* 1980, 13:91-94
60. Jarvinen TA, Kaariainen M, Jarvinen M, Kalimo H: Muscle strain injuries, *Curr Opin Rheumatol* 2000, 12:155-161

61. Gros J, Manceau M, Thome V, Marcelle C: A common somitic origin for embryonic muscle progenitors and satellite cells, *Nature* 2005, 435:954-958
62. Kassar-Duchossoy L, Giacone E, Gayraud-Morel B, Jory A, Gomes D, Tajbakhsh S: Pax3/Pax7 mark a novel population of primitive myogenic cells during development, *Genes Dev* 2005, 19:1426-1431
63. Relaix F, Rocancourt D, Mansouri A, Buckingham M: A Pax3/Pax7-dependent population of skeletal muscle progenitor cells, *Nature* 2005, 435:948-953
64. Le Grand F, Rudnicki MA: Skeletal muscle satellite cells and adult myogenesis, *Curr Opin Cell Biol* 2007, 19:628-633
65. McCroskery S, Thomas M, Maxwell L, Sharma M, Kambadur R: Myostatin negatively regulates satellite cell activation and self-renewal, *J Cell Biol* 2003, 162:1135-1147
66. McFarlane C, Hennebry A, Thomas M, Plummer E, Ling N, Sharma M, Kambadur R: Myostatin signals through Pax7 to regulate satellite cell self-renewal, *Exp Cell Res* 2008, 314:317-329
67. Deasy BM, Lu A, Tebbets JC, Feduska JM, Schugar RC, Pollett JB, Sun B, Urish KL, Gharaibeh BM, Cao B, Rubin RT, Huard J: A role for cell sex in stem cell-mediated skeletal muscle regeneration: female cells have higher muscle regeneration efficiency, *J Cell Biol* 2007, 177:73-86
68. Kunkel LM, Beggs AH, Hoffman EP: Molecular genetics of Duchenne and Becker muscular dystrophy: emphasis on improved diagnosis, *Clin Chem* 1989, 35:B21-24
69. Bieber FR, Hoffman EP: Duchenne and Becker muscular dystrophies: genetics, prenatal diagnosis, and future prospects, *Clin Perinatol* 1990, 17:845-865
70. Benabdallah BF, Bouchentouf M, Rousseau J, Bigey P, Michaud A, Chapdelaine P, Scherman D, Tremblay JP: Inhibiting myostatin with follistatin improves the success of myoblast transplantation in dystrophic mice, *Cell Transplant* 2008, 17:337-350
71. Gilson H, Schakman O, Kalista S, Lause P, Tsuchida K, Thissen JP: Follistatin induces muscle hypertrophy through satellite cell proliferation and inhibition of both myostatin and activin, *Am J Physiol Endocrinol Metab* 2009, 297:E157-164
72. Lee SJ: Quadrupling muscle mass in mice by targeting TGF-beta signaling pathways, *PLoS ONE* 2007, 2:e789

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## Abbreviations:

The abbreviations used in this manuscript include: TGF- $\beta$ 1, transforming growth factor –beta 1; ACVR2B, activin receptor II B; DMD, Duchenne Muscular Dystrophy; MyHC, myosin heavy chain; DMEM, Dulbecco's modified Eagle's medium; FBS, fetal bovine serum; P/S, penicillin/streptomycin; H&E, Hematoxylin and Eosin; DAPI, dihydrochloride 4', 6-Diamidino-2-phenylindole dihydrochloride; FLST, follistatin; FLST/OE, follistatin over-expressing; MSTN, myostatin; MPRO, myostatin propeptide; AAV2, adeno-associated virus serotype 2; MPCs, muscle progenitor cells; WT, wild type

## Figure Legends

Fig.1. Injured follistatin over-expressing (FLST/OE) skeletal muscles showed accelerated regeneration compared to their WT counterparts. A. H&E staining of cross sections of injured WT and FLST/OE skeletal muscle at 7, 14, 30 days and 1.5 years after laceration injury. Myofibers and nuclei were stained in red and black, respectively. Regenerating myofibers are characterized by centralized nuclei. Black scale bar represents 100  $\mu$ m. B. Distribution of diameters of regenerating myofibers in WT and FLST/OE skeletal muscle 7 (n = 3), 14 (n = 8), 30 (n = 8) days, and 1.5 years (n = 4) post-injury. Gray bars represent myofibers from WT mice while black bars represent myofibers from FLST/OE mice. Moreover, the gray arrowheads indicate mean diameters of regenerating fibers in WT muscle, while black arrowheads indicate mean diameters of regenerating fibers in FLST/OE muscle. C. Quantitation of the diameters of regenerating myofibers. The smallest diameters of over 300 non-adjacent myofiber per muscle were measured using Northern Eclipse Software. The mean diameters of regenerating fibers were shown to increase in both WT and FLST/OE muscles over time post-injury; however, the mean diameters of the FLST/OE fibers were significantly greater at all time points. ( $P < 0.05^*$ ,  $P < 0.01^{**}$ )

Fig.2. Fibrosis formation in the injured follistatin over-expressing (FLST/OE) muscle was reduced when compared to the injured WT muscle. Masson's trichrome staining was performed on sections of injured FLST/OE and WT muscle (myofibers in red; fibrosis in blue). A. Representative images of injured FLST/OE and WT muscle at 14 (n = 8) and 30 (n = 8) days after injury. There was significantly less fibrosis observed in the injured FLST/OE muscles than the WT muscles. B. Injured FLST/OE muscles developed significantly less fibrosis than did injured WT muscles. ( $P < 0.05^*$ ,  $P < 0.01^{**}$ )

Fig.3. Decreased myostatin (MSTN) expression and increased angiogenesis in injured follistatin over-expressing (FLST/OE) skeletal muscles. A. Immunohistochemistry was performed to detect MSTN (red) and collagen type IV (green) expression in injured WT and FLST/OE muscle. Collagen type IV was used to highlight the basal lamina of myofibers including, necrotic, intact, and regenerating myofibers. MSTN-positive signals were seen within some of the regenerating myofibers surrounded by the basal lamina (arrows) and some expression outside the basal lamina (arrowheads). Injured FLST/OE muscles contained less MSTN staining than did injured WT muscles. B. When we measured the relative MSTN positive signals and areas, we found that there was significantly more MSTN expression detected in the injured WT muscles than in injured FLST/OE muscles. C. CD31, an endothelial cell marker, was used to stain capillary-like structures in the injured muscles. D. There were a significantly greater number of CD31 positive signals present in the injured FLST/OE muscles than in the injured WT muscles (n = 8). ( $P < 0.05^*$ ,  $P < 0.01^{**}$ )

Fig.4. Characterization of muscle progenitor cells (MPCs). Seven follistatin over-expressing (FLST/OE) and 5 WT MPC populations were examined for Sca-1 expression, CD34 expression, and *in vitro* myogenic differentiation. A. Histograms showing wild variability in the percentages of Sca-1+&CD34+ Sca-1+, and CD34+ expressing cells among the MPC populations. B.

Quantitation revealed a significant increase in the Sca-1+ fraction in the FLST/OE MPC populations as compared with the WT MPC populations. C. Images on the left side are isotype controls; images on the right side are representative images of a flow cytometry dot plot showing that FLST/OE MPC populations consist of a larger proportion of Sca-1+ cells than the WT MPC populations (46.5% vs. 24%); D. Both FLST/OE and WT MPC populations underwent myogenic differentiation as labeled by MyHC (red) and DAPI (blue).

Fig.5. Follistatin over-expressing MPCs (FLST/OE MPCs) regenerated skeletal muscle more efficiently than WT MPCs, when transplanted into the GMs of mdx/SCID mice. A. Quantitation of engraftment in terms of the number of dystrophin-positive fibers regenerated by the FLST/OE and WT MPC populations. B. The overall mean number of dystrophin-positive myofibers was significantly greater for the FLST/OE MPCs ( $592.8 \pm 154.9$ ; Mean  $\pm$  SEM;  $n = 7$  FLST/OE MPC populations; 4 muscles per population) than for the WT MPC populations ( $195.6 \pm 65.4$ ; Mean  $\pm$  SEM;  $n = 5$  WT MPC populations; 4 muscles per population;  $P = 0.023^{**}$ , t-test). C. Representative engraftments showed that the transplanted MPCs regenerated dystrophin-positive myofibers (red) within dystrophic muscle. FLST/OE MPCs produced more dystrophin-positive myofibers than did WT MPCs. ( $P < 0.05^{*}$ ,  $P < 0.01^{**}$ )

Fig.6. Interactions between follistatin (FLST) and myostatin (MSTN), and FLST and activin A. A. As indicated by the fusion index (FI, the ratio of nuclei in myotubes to total nuclei), MSTN significantly inhibited C2C12 myoblast differentiation, but FLST counteracted MSTN and attenuated its inhibition of cellular differentiation. B. Without intervention, C2C12 myoblasts underwent myogenic differentiation in low serum medium as evidenced with MyHC (red) and DAPI (blue); Activin A significantly reduced muscle cell differentiation and the formation of myotubes in cell culture. C. FLST could neutralize the inhibitory effect of activin A on myoblast



differentiation as shown by FLST induced-restoration of differentiation. (n = 3;  $P < 0.05^*$ ,  $P < 0.01^{**}$ )

Fig.7. Follistatin (FLST) neutralized TGF- $\beta$ 1's activity on C2C12 myoblasts. A. Exemplary pictures of differentiation of C2C12 myoblasts treated by FLST alone, TGF- $\beta$ 1, and combinations of FLST and TGF- $\beta$ 1. Myotubes were visualized with MyHC (red), and DAPI (nuclei, blue). B. Our quantitative results showed that TGF- $\beta$ 1 significantly inhibited myogenic differentiation of C2C12 myoblasts. FLST was able to reverse TGF- $\beta$ 1-inhibited myogenic differentiation (n = 3). C. Western blot results showed that FLST decreased TGF- $\beta$ 1 expression in C2C12 myoblasts with or without the presence of exogenous TGF- $\beta$ 1. D. FLST also reduced the phosphorylation of SMAD2. E. FLST stimulated the expressions of the myogenic regulatory factors, MyoD, Myf5, and myogenin by myoblasts; the quantification of the western blots was indicated as normalized ratio of proteins of interest to  $\beta$ -actin, while controls were referred to as 1. ( $P < 0.05^*$ ,  $P < 0.01^{**}$ )

Fig.8. AAV2-MPRO improves skeletal muscle healing at 4 weeks after injury. (A) Masson's trichrome staining shows that fibrotic tissue (blue) exists at the muscle injury site (B) Fibrosis in the AAV2-MPRO-treated injured muscle is significantly decreased in comparison to the untreated control. (C) Collagen IV (green) and MPRO (red) double-immunostaining shows a strong MPRO signal in the cytoplasm of the fibers of AAV2-MPRO transduced muscle. (D) AAV2-MPRO transduced GMs gained significantly more weight than the GM controls. (E) H&E staining revealed obvious muscle hypertrophy in the AAV2-MPRO-treated injured muscles. (F) The increase in the average diameter of the regenerating myofibers in the AAV2-MPRO injected muscles was significant (Mean  $\pm$  SD;  $P < 0.01^{**}$ ). (G) Frequency histograms show the distribution of regenerating myofibers in the AAV-MPRO-treated and control muscles. Scale Bars: 100 $\mu$ m (E). Original magnifications: x100 (A); x200 (C, E).

Supplemental Figure S1. No significant difference was observed in the percentage of regenerating myofibers between FLST/OE and WT muscles at 7, 14, 30 days and 1.5 years after laceration injury.

Supplemental Figure S2. There was a reduction in activin A signal in the injured follistatin over-expressing (FLST/OE) skeletal muscles at 2 weeks post-laceration. Immunohistochemistry revealed positive activin A signals (red, arrowheads) and collagen IV (green) which outlines the regenerating myofibers. Injured FLST/OE muscles contained less activin A staining than did the injured WT muscles.

Supplemental Figure S3. Decreased p-SMAD 2/3 expression in injured follistatin over-expressing (FLST/OE) muscle compared to injured WT muscle. A. Immunohistochemistry was performed to detect p-SMAD 2/3 (red) and DAPI stained nuclei (blue) expression in injured WT and FLST/OE muscles. Injured FLST/OE muscles contained less p-SMAD 2/3 staining than did injured WT muscles 3 days after injury (Magnification: 200x, Insert 400x). B. When we measured the relative area of p-SMAD 2/3 positivity, we found that there was significantly more p-SMAD 2/3 expression detected in the injured WT muscles than in the injured FLST/OE muscles 3 days after injury. ( $P < 0.05^*$ )

Supplemental Figure S4. Follistatin treatment did not significantly change the myostatin mRNA levels in C2C12 myoblasts. Real time PCR was used to examine the myostatin mRNA levels of follistatin stimulated C2C12 myoblasts.

Supplemental Figure S5. Myostatin knockout-muscle progenitor cells (MSTN<sup>-/-</sup> MPCs) regenerated significantly more myofibers than WT MPCs, when injected into the gastrocnemius muscles of mdx/SCID mice. A. representative engraftments showed that transplanted MPCs

regenerated dystrophin-positive myofibers (red) within dystrophic muscle. B. Quantification of engraftment in terms of the number of dystrophin-positive fibers regenerated by MSTN<sup>-/-</sup> and WT MPC populations. C. The overall mean number of dystrophin-positive myofibers was significantly greater for the MSTN<sup>-/-</sup> MPCs than the WT MPCs. ( $P < 0.05^*$ )

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8 **ABSTRACT**

9 **Background:** Losartan, an angiotensin II receptor blocker (ARB), has been shown to be  
10 a clinically relevant transforming growth factor- $\beta$ 1 (TGF- $\beta$ 1) antagonist in many  
11 pathologies. Recently, we have shown that systemic administration of losartan reduced  
12 muscle fibrosis and increased the number of regenerating myofibers in a skeletal muscle  
13 injury model. However, the effective minimum dose of losartan required to improve  
14 muscle healing is still unknown and needed to be investigated so that it could eventually  
15 be translated into clinical use in humans.

16 **Purpose:** To investigate the minimum effective dose of losartan that can enhance muscle  
17 healing by both stimulating muscle regeneration and preventing fibrosis in an animal  
18 model and to evaluate losartan's effect on muscle function in two patients who suffered  
19 from hamstring muscle injuries. We believe that decreased fibrosis secondary to the  
20 antagonizing effects of TGF- $\beta$ 1 may expedite recovery.

21 **Study Design:** Controlled laboratory Study and Case Series

22 **Methods:** *In vitro*: C2C12 cells were cultured with angiotensin II or losartan, and the  
23 effects of these substances on myogenic differentiation were investigated.

24 *In vivo*: Thirty mice underwent bilateral anterior tibial muscle contusion. Varying  
25 concentrations of losartan (3, 10, 30, and 300mg/kg/day) were administrated immediately  
26 after injury. The mice were sacrificed 4 weeks after injury. Muscle regeneration and  
27 fibrosis were evaluated by histological analysis and functional recovery was measured by  
28 physiological testing.



*Case studies:* Two young male collegiate athletes with acute hamstring muscle injuries were treated with a 30 day course of oral losartan. Muscle strength and flexibility as a measure of function were evaluated over time.

**Results:** *In vitro:* Angiotensin II attenuated myogenic differentiation to a minimum of 59.8% compared to the untreated controls while the losartan stimulated cells showed a 150.0% increase in myogenic differentiation compared to the controls.

*In vivo:* According to histological analysis, the effective minimum dose of losartan to treat mice, that had received a skeletal muscle contusion injury, was 30mg/kg/day administrated immediately after injury. The peak twitch and tetanic forces, at four weeks post-injury, of the losartan groups were  $21.05 \pm 5.26$  and  $74.16 \pm 13.86 \text{ N/cm}^2$  respectively, while strength of the untreated control group was  $12.75 \pm 2.51$  and  $44.78 \pm 4.00 \text{ N/cm}^2$ , respectively.

*Case studies:* Both athletes showed improved muscle function after losartan treatment was added to standard care. There were no apparent side effects from the medication.

**Conclusion:** Oral administration of losartan showed significant improvement in muscle healing in a murine model and was well tolerated in two human hamstring injury cases without apparent side effects.

**Clinical Relevance:** Angiotensin II receptor blockers are clinically available, and may prove to be a safe, well tolerated improvement to current clinical treatment modalities of muscle injury.

**Keywords:**

Angiotensin II receptor blocker; muscle injury; muscle regeneration; fibrosis

52 **What is Known about the Subject:**

53 Losartan, an angiotensin II receptor blocker (ARB), has been shown to be a clinically  
54 relevant transforming growth factor- $\beta$ 1 (TGF- $\beta$ 1) antagonist in many pathologies.  
55 Angiotensin II receptor blockers are clinically available, and may prove to be a safe, well  
56 tolerated improvement to current clinical treatment modalities of skeletal muscle injury;  
57 however, the effective minimum dose of losartan required to improve muscle healing is  
58 still unknown and required investigation so that it can eventually be translated into  
59 clinical use in humans.

60

61 **Adds to Existing Knowledge:**

62 Recently, we have shown that systemic administration of losartan reduced muscle fibrosis  
63 and increased the number of regenerating myofibers in a skeletal muscle injury model.  
64 Oral administration of losartan showed significant improvement in muscle healing in a  
65 murine model and was well tolerated in two human hamstring injury cases without  
66 apparent side effects.

## INTRODUCTION

Muscle injuries constitute 10-55% of all injuries in sports medicine<sup>20</sup>. They can be caused by direct injury, including contusions, lacerations and strains, and by indirect injury related to ischemia, neurological dysfunction or medications. Of these, direct force-related injuries account for the majority (60%)<sup>38</sup> of injuries and acute hamstring injuries occur very frequently during sports activities<sup>6, 32</sup>. Such injuries are usually initially managed using the RICE (rest, ice, compression, and elevation) protocol, then progressive rehabilitation, which eventually includes eccentric strengthening. Despite employing what is considered appropriate care, severe muscle injuries typically result in the formation of dense scar tissue (fibrosis) that impairs muscle function, which can lead to muscle contracture, chronic pain and diminishes the individual's ability to achieve full functional recovery and their return to prior levels of performance.

It is well known that transforming growth factor- $\beta$ 1 (TGF- $\beta$ 1) plays a crucial role in tissue fibrosis<sup>43, 44</sup>, particularly in skeletal muscle<sup>1, 5, 26, 45</sup> and warrants attention as a key target for anti-fibrotic applications. With this in mind, we have previously investigated the effects of antagonizing TGF- $\beta$ 1 with decorin<sup>25, 41, 46</sup>, relaxin<sup>47</sup>, gamma interferon<sup>24</sup>, and suramin<sup>12, 52</sup> and have shown their ability to decrease fibrosis and increase muscle regeneration after skeletal muscle injury. Unfortunately, many of the anti-fibrotic agents that have been investigated in the laboratory setting cannot readily be translated to clinical practice due to the lack of an oral formulation, Food and Drug Administration (FDA) approval status, and/or a relatively severe side-effect profile.

Losartan is the first orally active, non-peptide angiotensin II (ANGII) type 1 receptor (AT1) blocker (ARB) and is well known as a class of antihypertensive drugs. It

is widely used for the treatment of hypertension and congestive heart failure with a low-incidence of adverse side effects<sup>18</sup>, and is commercially available in an oral formulation. Its TGF- $\beta$ 1 antagonist effect has been shown to be clinically relevant in many other disease states such as renal disease, pulmonary fibrosis, cardiomyopathies, and aortic aneurysm<sup>14, 19, 27, 41, 42</sup>. Additionally, Cohn et al.<sup>8</sup> has shown that losartan can normalize muscle architecture, repair, and function in multiple myopathic states (e.g. Marfan syndrome and Duchenne muscular dystrophy). Moreover, ACE inhibitors have also been shown to improve muscle mass in older patients<sup>12</sup>. Finally, in a murine model of muscle laceration, we demonstrated the up-regulation of AT1 in posttraumatic skeletal muscle tissue<sup>4</sup> as well as the fact that systemic losartan administration reduced muscle fibrosis and increased the number of regenerating myofibers<sup>4</sup>.

The optimal dose of losartan for the prevention of muscle fibrosis after skeletal muscle injury has not yet been determined nor have the functional improvements been tested. The manufacturer's recommended starting dose of losartan for antihypertensive and congestive heart failure therapy is 50mg/day, and clinical doses range from 25mg/day to 100mg/day; however, the effective minimum dose of losartan to improve muscle healing is still unknown. In this study, we sought to investigate the minimum effective dose of losartan necessary to improve skeletal muscle healing after injury in a controlled laboratory setting. We also investigated the effect of the standard losartan dose as an adjuvant for treating acute muscle strain injuries in two patient-athletes.

## MATERIALS AND METHODS

### *I – In Vitro* Potential of Angiotensin II and Losartan on C2C12 Myoblasts and Fibroblasts

#### *Cell Culture*

C2C12 myoblast cells, a well-known myoblast cell line, were purchased from the American Type Culture Collection (Manassas, VA). C2C12 cells were plated onto 12-well plates at a density of 10,000 cells/well.. The previously published preplate technique was used to isolate fibroblasts from early adhering populations of muscle cells<sup>17, 35</sup>. Isolated fibroblasts were plated onto 24-well plates at a density of 10,000 cells/well. The cells were cultured with Dulbecco's modified Eagle's medium (DMEM) (Invitrogen, Carlsbad, CA) containing 10% fetal bovine serum (FBS) (Invitrogen), and 1% penicillin/streptomycin (P/S) (Invitrogen)..

#### *Effect of ANGII and Losartan on TGF- $\beta$ 1 Expression by Fibroblasts*

A TGF- $\beta$ 1 immunoassay (mouse TGF-  $\beta$ 1 DuoSet ELISA Development System, R&D systems, Minneapolis, MN) was performed to detect the effect that ANGII and losartan had on fibroblasts. After a 24-hour incubation period, the medium was completely removed and replaced with serum-free medium supplemented with a serum replacement (Sigma, St. Louis, MO) containing different concentration of human ANGII ( $10^{-8}$ ,  $10^{-7}$ , and  $10^{-6}$  mol/L) (Sigma) or losartan ( $10^{-8}$  and  $10^{-6}$  mol/L) (Cozaar<sup>®</sup>; Merck, Whitehouse Station, NJ). After 8 or 24 hour incubations, the medium was collected and the cells were counted using a hemacytometer. The manufacture's protocol was then



used to determine the amount of TGF- $\beta$ 1 in the medium, which was expressed as picograms (pg) of TGF-  $\beta$ 1/10,000cells.

#### *Effects of ANGII and Losartan on C2C12 Myoblasts*

After a 24-hour incubation period, the medium was removed and replaced by low serum-containing medium (DMEM containing 2% horse serum [HS] [Invitrogen]) containing different concentration of human ANGII ( $10^{-10}$ ,  $10^{-8}$ , and  $10^{-6}$ mol/L) or losartan ( $10^{-10}$ ,  $10^{-8}$ , and  $10^{-6}$ mol/L). Medium was replaced with fresh medium (containing the same concentration of ANGII or losartan) every 48 hours. All cells were grown for a total of 5 days. To quantify the differentiation of the C2C12 cells, cells were fixed in cold methanol for 2 minutes and washed in Dulbecco's phosphate-buffered saline (PBS) for 10 minutes at room temperature (RT). Samples were washed twice in PBS, then incubated in blocking buffer (10% HS in PBS) for 30 minutes at RT. Cells were incubated overnight at 4°C with mouse monoclonal anti-skeletal fast myosin heavy chain antibody (clone MY-32, Sigma) in 2% HS in PBS. After washing with PBS, samples were incubated with a secondary donkey anti-mouse antibody which was conjugated with Alexa Fluor 594 (Invitrogen) in 2% HS for 40 minutes at RT. Cell nuclei were stained with 4', 6-diamidino-2-phenylindole dihydrochloride (DAPI) (Sigma) for 10 minutes at RT. The fusion index (ratio of nuclei in myotubes to total number of nuclei) was calculated to evaluate cell myogenic differentiation capacity.

## **2 – *In Vivo* Evaluation of the Histological and Physiological Effects of Losartan on Muscle Healing After Contusion Injury**

## *Animal Model*

The policies and procedures followed for the animal experimentation performed in this study are in accordance with those detailed by the US department of Health and Human Services and the National Institutes of Health *Guide for the Care and Use of Laboratory Animals*. All experimental protocols were approved by the Animal Research and Care Committee of the author's institution. Thirty-three normal mice (C57BL/6J, Jackson Laboratory, Bar Harbor and National Cancer Institute at Frederick, Frederick, MD), aged 8-10 weeks weighing 21.4 to 25.8g, were used in this experiment.

A muscle contusion injury were established bilaterally, in 30 mice as described previously<sup>25 10 30</sup>. Briefly, the mice were anesthetized with 1.0 to 1.5% isoflurane (Abbott Laboratories, North Chicago, Illinois) in 100% O<sub>2</sub> gas and the animal's hindlimb was positioned by extending the knee and plantar flexing the ankle to 90 degrees. A 16.2g/1.6cm stainless steel ball (Small Parts Inc, Miami Lakes, FL) was dropped from a height of 100cm onto an impactor that reached the mouse's tibialis anterior (TA) muscle. This muscle contusion created is a high-energy blunt injury that results in a large hematoma followed by muscle regeneration and fibrosis<sup>10 25</sup>, in a similar fashion as seen in humans<sup>13</sup>. The mice were sacrificed after 4 weeks to evaluate, physiologically and histologically, muscle healing. One-leg of each mouse (6 muscles/group) was assessed physiologically. The contra-lateral hind limb (6 muscles/group) was isolated for histological analysis.

## *Drug Administration*

All injured mice were randomly assigned to 1 of 5 groups (6 mice/group) on the basis of different concentration of oral losartan. The control group was supplied with normal drinking water while the other 4 treated groups had commercially available losartan (Cozaar<sup>®</sup>) dissolved in their drinking water at dosage levels of 3, 10 (lower dose groups), 30, or 300mg/kg/day (higher dose groups). These doses were calculated based on the body weight and the average daily fluid intake of the mice which had been monitored once a week before injury. The dose of losartan at 10mg/kg/day is equivalent to the clinical doses for the treatment of high blood pressure (50mg/day) and the dose of 3mg/kg/day is considered lower than the minimum clinical dose for treating human hypertension (25mg/day)<sup>36</sup>. All animals were caged separately and allowed access to the water or losartan solutions *ad libitum* from the time of injury to sacrifice.

#### *Physiological Evaluation of Muscle Strength Recovery after Losartan Therapy*

Physiological testing was performed, four weeks after injury (one limb per mouse, n=6 muscles/group), by a modified *in situ* force testing protocol as described by Dellorusso et al.<sup>11</sup> The animals were anesthetized with 1.0 to 1.5% isoflurane (Abbott Laboratories), placed on a heated platform (37°C) and the knee and foot were secured to the platform with cloth tape to better stabilize the hind limb. The TA's distal tendon was exposed, by an incision at the ankle, was sutured securely as close to the muscle attachment as possible with 5-0 silk suture and the tendon was cut several millimeters distal to the end of the muscle. The exposed tendon and muscle were kept moist by periodic applications of isotonic saline. The tendon was securely tied to the lever arm of a custom made transducer and data acquisition hardware (NI USB-6215, National

Instruments. Austin, TX). The transducer monitored the force developed by the muscle. All data were displayed and stored on a computer by using a LabView (National Instruments) custom made program.

Anterior crural muscles were stimulated through the peroneal nerve by electrodes inserted via a small incision; the TA muscle was stimulated with 0.2 ms pulses. Stimulation voltage and subsequently muscle length ( $L_0$ ) were adjusted for maximum isometric twitch force (peak twitch;  $P_t$ ). While held at  $L_0$ , the muscle was stimulated at increasing frequencies, stepwise from 150Hz by 50Hz, until a maximum force ( $P_0$ ) was monitored. A one- to two-minute rest period was allowed between each tetanic contraction. Then, the entire TA muscle was exposed and the muscle length was measured with a digital caliper. Optimum fiber length ( $L_f$ ) was calculated by the TA  $L_f/L_0$  ratio of 0.6<sup>7</sup>. After the evaluation, the muscle was removed and the mice were euthanized. The tendon and suture were removed and the muscle was weighed. Total muscle cross-sectional area (CSA) of TA muscle was calculated by dividing muscle mass by the product of  $L_f$  and 1.06mg/mm<sup>3</sup>, the density of mammalian skeletal muscle. Specific  $P_t$  and  $P_0$  were calculated by dividing  $P_t$  and  $P_0$  by CSA (N/cm<sup>2</sup>). Physiological analysis was also performed in three normal animals as a non-injured group.

#### *Evaluation of Muscle Regeneration after Losartan Therapy*

Isolated TA muscles were frozen rapidly in 2-methylbutane pre-cooled with liquid nitrogen. Specimens were kept at -80°C until sectioning. Serial cryosections of 8μm thickness were stained with hematoxylin and eosin (H&E) to evaluate the number of regenerating myofibers. The total number of centronucleated myofibers, which are

considered to be the regenerating myofibers<sup>22 37 28</sup>, was quantified within the injury site by using 10 random 200x high-powered fields selected from each sample<sup>16 15 29 30</sup>. Results from the control and each treatment groups were compared.

### *Evaluation of Fibrosis after Losartan Therapy*

Masson's Modified IMEB Trichrome stain Kit (IMEB Inc, Chicago, Illinois) was used to measure areas of fibrotic tissue within the injury sites. After staining, the ratio of the fibrotic area to the total cross-sectional area of 10 randomly selected sections was calculated to estimate the fibrosis formation using Northern Eclipse software (Empix Imagine Inc., Cheekatawaga, NY) in accordance with previously described protocols<sup>16 15 29 30</sup>.

### *Statistical Analysis*

All of the results of this study were expressed as the mean± standard deviation. The results of the *in vitro* studies were analyzed using the Kruskal-Wallis test with the Mann-Whitney U-test used as a post hoc test. To determine the minimum effective dose of losartan *in vivo*, we analyzed the results using Williams' multiple comparison. The differences of mean specific twitch and tetanic force between the control muscle (injured/non-treated) and normal muscle (non-injured) were analyzed with Kruskal-Wallis test. Statistical significance was defined as  $p < 0.05$ .

### *3 – Case studies*

Two adult males (21 and 22 years old) with acute/recurrent hamstring muscle injuries were evaluated and treated with losartan in addition to standard rehabilitation. Both subjects were healthy college athletes (football and ultimate frisbee) without other injuries or co-morbidities.

At the initial evaluation in the clinic, a history and physical examination were performed and each patient-athlete underwent testing that included measurements of isometric hamstring muscle force and flexibility. Isometric force was evaluated with a hand-held dynamometer (Lafayette Instrument Inc); the subject was placed in a prone position and the hand-held dynamometer was placed over the Achilles tendon at the level just proximal to the medial malleolus. Both legs were tested and three trials were performed with the knee at 30 and 90° of knee flexion. Each trial was held for 3 to 5 seconds as the subject attempted to generate maximal force while the examiner exerted resistance to prevent movement. The averages of the three trials at each angle of knee flexion were calculated. Strength of the injured hamstring muscle was expressed as a percentage of the uninjured leg. Flexibility of the hamstrings was measured with a goniometer, with the individual in the supine position, as the amount of available knee extension with the hip flexed to 90°. The patients also had plain radiographs of the pelvis, to rule out fracture of the ischial tuberosity and magnetic resonance imaging (MRI) (1.5T; GE-Sigma, Waukesha, WI, USA) of the involved muscles was performed to better characterize the injury.

After obtaining the patients' consent for treatment, they were started on a 30-day course of losartan (Cozaar<sup>®</sup>) at the manufacturer's recommended oral daily dose of 50mg. In addition to the medication, the subjects underwent routine standard of care



rehabilitation supervised by a physical therapist and/or athletic trainer. The rehabilitation program included the use of superficial heat, flexibility and strengthening exercises for the hamstring muscles. The strengthening exercises were progressed from isometric to concentric and then eccentric exercises with resistance as tolerated by the athlete. Return to sports activities progressed from jogging to running and sprinting. The patients were evaluated every 7 days by a study physician (YC) that included measurement of blood pressure and hamstring flexibility and strength as described above. At the conclusion of treatment both patients underwent testing on an isokinetic dynamometer (Biodex II; Shirley, New York) at 60 and 180° per second to assess the torque generating capacity of the hamstring and quadriceps muscles.

## RESULTS

### ***1 – In Vitro Potential of Angiotensin II and Losartan in C2C12 Myoblasts and Fibroblasts***

#### *Effects of ANGII and Losartan on TGF- $\beta$ 1 Expression by Fibroblasts*

Fibroblasts, isolated from normal skeletal muscle, up-regulated the expression of TGF- $\beta$ 1, in a dose dependent manner, when cultured in a medium containing  $10^{-7}$  and  $10^{-6}$ mol/L of ANGII at 24 hours after exposure ( $53.3 \pm 0.8$  and  $89.5 \pm 3.3$ pg/10,000cells, respectively). Both concentrations of losartan ( $10^{-7}$  and  $10^{-6}$ mol/L) blocked TGF- $\beta$ 1 expression induced by  $10^{-6}$ mol/L of ANGII ( $36.9 \pm 2.7$  and  $25.9 \pm 2.43$ pg/10,000cells, respectively) (Figure 1).

#### *Effects of Angiotensin II and Losartan on Myoblasts*

294 The fusion index of C2C12 cells in the groups exposed to  $10^{-10}$ ,  $10^{-8}$ , and  $10^{-6}$   
295 mol/L of ANGII were significantly lower ( $0.23 \pm 0.06$ ,  $0.27 \pm 0.08$ , and  $0.23 \pm 0.06$ ,  
296 respectively) than the control group ( $0.35 \pm 0.07$ ). On the other hand, groups treated with  
297 losartan ( $10^{-10}$ ,  $10^{-8}$ , and  $10^{-6}$  mol/L) showed higher fusion indices ( $0.17 \pm 0.03$ ,  $0.16 \pm 0.04$ ,  
298 and  $0.17 \pm 0.05$ , respectively) than the control group ( $0.12 \pm 0.04$ ) (Figure 2).

299

## 300 **2 – *In vivo* Evaluation of the Histological and Physiological Effects of Losartan on**

### 301 **Muscle Healing after Contusion Injury**

#### 302 *Losartan Improved Muscle Strength Recovery after Contusion Injury.*

303 Results from the physiological evaluations performed at four weeks post-injury  
304 are shown in Table 1. The control injured group showed significantly less specific peak  
305 twitch and tetanic forces ( $12.75 \pm 2.51$  and  $44.78 \pm 4.00 \text{ N/cm}^2$ , respectively) when  
306 compared with the non-injured group ( $19.24 \pm 0.73$  and  $58.56 \pm 11.51 \text{ N/cm}^2$ , respectively).  
307 Specific peak twitch and tetanic forces in the higher losartan dosage groups (30 and  
308 300mg/kg/day) were greater than control group, while the lower dosage groups did not  
309 improve muscle strength on specific peak twitch and tetanic forces when compared with  
310 the control group. The group treated with 30mg/kg/day of losartan showed the best  
311 muscular strength recovery on both peak twitch and tetanic forces among the groups. The  
312 effective minimum doses for specific  $P_t$  and  $P_0$  were the 30mg/kg/day group.

313

#### 314 *Effect of Losartan on Myofiber Regeneration after Contusion Injury*

315 All the centronucleated regenerating myofibers in the injured muscle were  
316 counted and compared to the control group (Figure 3F). The group treated with

300mg/kg/day of losartan showed the best results among groups ( $194.52 \pm 68.18$ /hpf) (Figure 3E). The effect of losartan on myofiber regeneration decreased gradually with reductions in the dose of losartan. The effective minimum dose of losartan on muscle regeneration was 30mg/kg/day ( $p=0.046$ ). There were no significant differences between the lower dosage groups (3 and 10mg/kg/day) ( $108.83 \pm 27.25$  and  $94.47 \pm 25.31$ /hpf, respectively) and the control group ( $91.32 \pm 22.95$ /hpf).

#### *Effect of Losartan on Muscle Fibrosis after Contusion Injury*

The area of fibrotic scar tissue was evaluated and compared to the control group (Figure 4F). The mean area of fibrosis of the control group within the zone of injury was  $12.80 \pm 4.98\%$ . The higher losartan dosage groups (30 and 300mg/kg/day) had significantly less fibrosis ( $9.82 \pm 4.93$  and  $8.48 \pm 3.82\%$ , respectively) when compared with the control group ( $p=0.001$  and  $0.0002$ , respectively) (Figure 4D, E) while the lower losartan dosage groups did not show any significant difference.

### **3 – Case studies**

At the time of initial presentation, both patients described a similar hamstring injury approximately 10 weeks prior to the current injury. They had been treated with relative rest and rehabilitation and had returned to full activity without residual symptoms. The remainders of their histories were similar. Exam revealed healthy, active young men who walked without an antalgic gait. Mild ecchymosis was present in the distal posterior thigh, and each had significant tenderness to palpation at the mid substance biceps

femoris, without obvious palpable defect. Weakness and pain was reproduced with hamstring manual muscle testing. Neurovascular exam was normal.

X-rays were similar and the MRIs confirmed in both patients a partial thickness tear of the biceps femoris with surrounding edema. No fracture or significant hematoma was present (Figure 5). Serial isometric strength and flexibility measurements, performed at different time points, are summarized in table 2.

In addition to the isometric tests, isokinetic tests were also performed, and the results for the injured side were essentially equal to the uninjured side treated with losartan after 9 weeks or 7 weeks. **For patient #1**, at 9 weeks after the injury, the peak hamstring torque of the injured side was 96% at 60°/sec and 107% of the injured side at 180°/sec. In terms of total work performed at 180°/sec there was a 9.8% deficit in total work across the 10 repetitions in comparison to the uninjured side. The patient exhibited more fatigue of the hamstrings on the injured side at 180°/sec. Comparing the work in the 1st 1/3 of the repetitions to the last 1/3 of the repetitions, the decrease in hamstring torque on the injured side was 19% compared to 8.3% on the uninjured side. **For patient #2**, 7 weeks after the injury, peak hamstring torque of the injured side was 92.5% at 60°/sec and 100.4% at 180°/sec compared to the uninjured side. At 180°/sec there was a 6.2% increase in total work across the 10 repetitions that were performed. Contrary to patient #1, fatigue of the injured leg was less than the uninjured leg at 60°/sec (10.3% vs. 17.3%) and at 180°/sec (22.1% vs. 31.2% at 180°/sec).

Both patients reported no side effects while they were taking the losartan and remained normotensive throughout the 30 day course of the medication.

## DISCUSSION

This study has shown, *in vitro* and *in vivo* the positive effects of an ARB on muscle healing after injury. We have also demonstrated tolerability and the possibility of improved muscle healing with the use of losartan in two clinical cases. The *in vitro* section of this study showed that losartan blocks the expression of TGF- $\beta$ 1 and improves muscle cell fusion indices. We also demonstrated in, a mouse muscle contusion model, that the systemic administration of losartan immediately after injury would increase the number of regenerating myofibers and reduce fibrotic scar formation at the injury site, and ultimately increase the recovery of muscular strength when compared with the injured untreated control group 4 weeks post injury. Moreover, we have described the clinical use of losartan as an adjuvant treatment in healthy athletes with a recurrent grade II (partial tear) hamstring injury. The subjects tolerated the course of losartan well and demonstrated recovery of normal flexibility and strength when compared to the contralateral leg.

More than 90% of muscle injuries are caused either by contusion or by excessive strain of the muscle<sup>24</sup>. The morbidity associated with these injuries leads to loss of valuable time in training and competition for an athlete and time lost from work in the occupational patient. Repeat injury is very common and it is known that the structural changes that occur in skeletal muscle after injury contribute to the risk of re-injury<sup>39</sup>. Additionally, it is felt that improved muscle regeneration and reduced fibrosis correlates with enhanced function. Functional recovery after muscle injury is the most important factor for determining the success of therapy and the possibility of translating the technology into clinical application. Our results showed that 30mg/kg/day of losartan was

the optimum dose to improve muscle strength in mice when it was administrated immediately after injury. The physiological results corresponded to the effective minimum dose on histological models as well. Our results suggest that 300mg/kg/day of losartan lead to greater improvements in muscle regeneration and decreased fibrosis when compared to 30mg/kg/day, however, this higher dose of losartan did not seem to be necessary for functional recovery. As expected, the lower dose groups did not show significant improvements in the specific peak twitch and tetanic forces.

Our previous research has shown that muscle healing proceeds through four distinct and sequential phases: necrosis/degeneration, inflammation, regeneration, and finally fibrous tissue formation<sup>20</sup>. The peak of myofiber regeneration and scar tissue formation are approximately 2 and 4 weeks after injury respectively<sup>20, 21</sup>, after the peak of capillary generation that occurs at approximately 7 days<sup>31</sup>. Angiogenesis promotes muscle regeneration after the phases of degeneration and inflammation, and is a prerequisite for the subsequent morphological and functional recovery of the injured muscle<sup>23</sup>. Moreover, ANGII plays a critical role in the induction of angiogenesis in skeletal muscle via AT1<sup>33</sup>. Thus, the activation of the rennin angiotensin system (RAS) in the early phase of healing may be required to promote angiogenesis which is required for tissue regeneration to. With these points in mind, in order to provide the optimal benefit with ARB treatment, we postulate ARB therapy should not be immediately initiated after injury but instead started several days after injury so that it can reduce ANGII induced apoptosis, differential inhibition of myocytes and tissue fibrosis. Moreover, the ARB therapy must begin prior to the deposition of fibrous tissue which occurs approximately 4 weeks after injury. This approach may make it possible to further reduce the effective



minimum dose described in this study; however, additional studies are required to confirm this hypothesis. In addition, the contusion injury created in the experimental animals was massive and far more severe than what are typically seen in most human injuries found in a sports medicine practice which may also make it possible to further reduce the dose given to human subjects.

In both patients we initiated losartan treatment after the acute period of necrosis/degeneration and inflammation (10 days after injury for the first patient and 5 days after injury for the second patient). Both patients demonstrated normal hamstring flexibility and strength by 9 weeks after injury and were without activity-limiting pain at that time. While meeting this criteria would normally correlate with an appropriate time to return to athletics, both athletes suffered injury at the end of their season and thus a return to sports was not a primary end point. To date (> 6 months) neither individual has suffered any further injury to the hamstring muscles, which may represent the most important feature of the study i.e. eliminating the potential of re-injury.

Extrapolating the time to return to play for hamstring injuries from the previous studies is a difficult and an inexact task as evidenced by the many variables involved and a wide range of time reported in the studies ranging from mean of 14 days to 62 weeks<sup>3 6, 34 40 9 2</sup>. Data on lost time from competition for recurrent hamstring injuries is even more limited and two groups have noted that recurrent injuries prolonged the duration of rehabilitation by 33% (Powell and Zarins, 1989-1998, 1696 injuries in NFL players as reported at 2002 NFLTP meeting) to 79%<sup>6</sup> compared to new injuries. However, these studies do not accurately report the severity and the exact location of the injuries. For our patients, both would have been able to return to full sports participation within 9 weeks

431 and in our clinical experience this is a shorter period of time than what we have observed  
432 in the past, for young athletic patients with a similar degree of recurrent injury.

433 We are encouraged by the results of these interventions; however we recognize  
434 the limitations of making treatment decisions based on case reports. We believe that  
435 translational clinical research, in the form of a prospective, blinded, placebo controlled  
436 randomized clinical trial is necessary to determine the benefits of losartan use in  
437 comparison to conventional approaches for the treatment of hamstring muscle injuries  
438 alone. This research should consider the effects of the ARB on recovery of hamstring  
439 flexibility and strength, degree of fibrosis, time to return to full participation in sports and  
440 the frequency of recurrent injury, as well as any adverse effects encountered by otherwise  
441 healthy individuals.

## REFERENCES

1. Amemiya K, Semino-Mora C, Granger RP, Dalakas MC. Downregulation of TGF-beta1 mRNA and protein in the muscles of patients with inflammatory myopathies after treatment with high-dose intravenous immunoglobulin. *Clin Immunol.* 2000;94(2):99-104.
2. Askling CM, Tengvar M, Saartok T, Thorstensson A. Acute first-time hamstring strains during slow-speed stretching: clinical, magnetic resonance imaging, and recovery characteristics. *Am J Sports Med.* 2007;35(10):1716-1724.
3. Askling CM, Tengvar M, Saartok T, Thorstensson A. Proximal hamstring strains of stretching type in different sports: injury situations, clinical and magnetic resonance imaging characteristics, and return to sport. *Am J Sports Med.* 2008;36(9):1799-1804.
4. Bedair HS, Karthikeyan T, Quintero A, Li Y, Huard J. Angiotensin II receptor blockade administered after injury improves muscle regeneration and decreases fibrosis in normal skeletal muscle. *Am J Sports Med.* 2008;36(8):1548-1554.
5. Bernasconi P, Torchiana E, Confalonieri P, et al. Expression of transforming growth factor-beta 1 in dystrophic patient muscles correlates with fibrosis. Pathogenetic role of a fibrogenic cytokine. *J Clin Invest.* 1995;96(2):1137-1144.
6. Brooks JH, Fuller CW, Kemp SP, Reddin DB. Incidence, risk, and prevention of hamstring muscle injuries in professional rugby union. *Am J Sports Med.* 2006;34(8):1297-1306.
7. Burkholder TJ, Fingado B, Baron S, Lieber RL. Relationship between muscle fiber types and sizes and muscle architectural properties in the mouse hindlimb. *J Morphol.* 1994;221(2):177-190.
8. Cohn RD, van Erp C, Habashi JP, et al. Angiotensin II type 1 receptor blockade attenuates TGF-beta-induced failure of muscle regeneration in multiple myopathic states. *Nat Med.* 2007;13(2):204-210.
9. Connell DA, Schneider-Kolsky ME, Hoving JL, et al. Longitudinal study comparing sonographic and MRI assessments of acute and healing hamstring injuries. *AJR Am J Roentgenol.* 2004;183(4):975-984.
10. Crisco JJ, Jokl P, Heinen GT, Connell MD, Panjabi MM. A muscle contusion injury model. Biomechanics, physiology, and histology. *Am J Sports Med.* 1994;22(5):702-710.
11. Dellorusso C, Crawford RW, Chamberlain JS, Brooks SV. Tibialis anterior muscles in mdx mice are highly susceptible to contraction-induced injury. *J Muscle Res Cell Motil.* 2001;22(5):467-475.
12. Di Bari M, van de Poll-Franse LV, Onder G, et al. Antihypertensive medications and differences in muscle mass in older persons: the Health, Aging and Body Composition Study. *J Am Geriatr Soc.* 2004;52(6):961-966.
13. Diaz JA, Fischer DA, Rettig AC, Davis TJ, Shelbourne KD. Severe quadriceps muscle contusions in athletes. A report of three cases. *Am J Sports Med.* 2003;31(2):289-293.

- 487 **14.** el-Agroudy AE, Hassan NA, Foda MA, et al. Effect of angiotensin II receptor  
488 blocker on plasma levels of TGF-beta 1 and interstitial fibrosis in hypertensive  
489 kidney transplant patients. *Am J Nephrol.* 2003;23(5):300-306.
- 490 **15.** Foster W, Li Y, Usas A, Somogyi G, Huard J. Gamma interferon as an  
491 antifibrosis agent in skeletal muscle. *J Orthop Res.* 2003;21(5):798-804.
- 492 **16.** Fukushima K, Badlani N, Usas A, Riano F, Fu F, Huard J. The use of an  
493 antifibrosis agent to improve muscle recovery after laceration. *Am J Sports Med.*  
494 2001;29(4):394-402.
- 495 **17.** Gharaibeh B, Lu A, Tebbets J, et al. Isolation of a slowly adhering cell fraction  
496 containing stem cells from murine skeletal muscle by the preplate technique. *Nat*  
497 *Protoc.* 2008;3(9):1501-1509.
- 498 **18.** Goldberg MR, Tanaka W, Barchowsky A, et al. Effects of losartan on blood  
499 pressure, plasma renin activity, and angiotensin II in volunteers. *Hypertension.*  
500 1993;21(5):704-713.
- 501 **19.** Habashi JP, Judge DP, Holm TM, et al. Losartan, an AT1 antagonist, prevents  
502 aortic aneurysm in a mouse model of Marfan syndrome. *Science.*  
503 2006;312(5770):117-121.
- 504 **20.** Huard J, Li Y, Fu FH. Muscle injuries and repair: current trends in research. *J*  
505 *Bone Joint Surg Am.* 2002;84-A(5):822-832.
- 506 **21.** Huard J, Yokoyama T, Pruchnic R, et al. Muscle-derived cell-mediated ex vivo  
507 gene therapy for urological dysfunction. *Gene Ther.* 2002;9(23):1617-1626.
- 508 **22.** Hurme T, Kalimo H. Activation of myogenic precursor cells after muscle injury.  
509 *Med Sci Sports Exerc.* 1992;24(2):197-205.
- 510 **23.** Jarvinen M. Healing of a crush injury in rat striated muscle. 3. A micro-  
511 angiographical study of the effect of early mobilization and immobilization on  
512 capillary ingrowth. *Acta Pathol Microbiol Scand A.* 1976;84(1):85-94.
- 513 **24.** Jarvinen MJ, Lehto MU. The effects of early mobilisation and immobilisation on  
514 the healing process following muscle injuries. *Sports Med.* 1993;15(2):78-89.
- 515 **25.** Kasemkijwattana C, Menetrey J, Somogyi G, et al. Development of approaches to  
516 improve the healing following muscle contusion. *Cell Transplant.* 1998;7(6):585-  
517 598.
- 518 **26.** Li Y, Huard J. Differentiation of muscle-derived cells into myofibroblasts in  
519 injured skeletal muscle. *Am J Pathol.* 2002;161(3):895-907.
- 520 **27.** Lim DS, Lutucuta S, Bachiredy P, et al. Angiotensin II blockade reverses  
521 myocardial fibrosis in a transgenic mouse model of human hypertrophic  
522 cardiomyopathy. *Circulation.* 2001;103(6):789-791.
- 523 **28.** McCormick KM, Schultz E. Role of satellite cells in altering myosin expression  
524 during avian skeletal muscle hypertrophy. *Dev Dyn.* 1994;199(1):52-63.
- 525 **29.** Menetrey J, Kasemkijwattana C, Fu FH, Moreland MS, Huard J. Suturing versus  
526 immobilization of a muscle laceration. A morphological and functional study in a  
527 mouse model. *Am J Sports Med.* 1999;27(2):222-229.
- 528 **30.** Nozaki M, Li Y, Zhu J, et al. Improved muscle healing after contusion injury by  
529 the inhibitory effect of suramin on myostatin, a negative regulator of muscle  
530 growth. *Am J Sports Med.* 2008;36(12):2354-2362.

- 531 **31.** Ochoa O, Sun D, Reyes-Reyna SM, et al. Delayed angiogenesis and VEGF  
532 production in CCR2-/- mice during impaired skeletal muscle regeneration. *Am J*  
533 *Physiol Regul Integr Comp Physiol.* 2007;293(2):R651-661.
- 534 **32.** Orchard J, Seward H. Epidemiology of injuries in the Australian Football League,  
535 seasons 1997-2000. *Br J Sports Med.* 2002;36(1):39-44.
- 536 **33.** Petersen MC, Greene AS. Angiotensin II is a critical mediator of prazosin-  
537 induced angiogenesis in skeletal muscle. *Microcirculation.* 2007;14(6):583-591.
- 538 **34.** Pomeranz SJ, Heidt RS, Jr. MR imaging in the prognostication of hamstring  
539 injury. Work in progress. *Radiology.* 1993;189(3):897-900.
- 540 **35.** Qu-Petersen Z, Deasy B, Jankowski R, et al. Identification of a novel population  
541 of muscle stem cells in mice: potential for muscle regeneration. *J Cell Biol.*  
542 2002;157(5):851-864.
- 543 **36.** Sasaki M, Uehara S, Ohta H, et al. Losartan ameliorates progression of  
544 glomerular structural changes in diabetic KKAy mice. *Life Sci.* 2004;75(7):869-  
545 880.
- 546 **37.** Schultz E, McCormick KM. Skeletal muscle satellite cells. *Rev Physiol Biochem*  
547 *Pharmacol.* 1994;123:213-257.
- 548 **38.** Shanmugam C, Maffulli N. Sports injuries in children. *Br Med Bull.* 2008;86:33-  
549 57.
- 550 **39.** Silder A, Heiderscheid BC, Thelen DG, Enright T, Tuite MJ. MR observations of  
551 long-term musculotendon remodeling following a hamstring strain injury. *Skeletal*  
552 *Radiol.* 2008;37(12):1101-1109.
- 553 **40.** Slavotinek JP, Verrall GM, Fon GT. Hamstring injury in athletes: using MR  
554 imaging measurements to compare extent of muscle injury with amount of time  
555 lost from competition. *AJR Am J Roentgenol.* 2002;179(6):1621-1628.
- 556 **41.** Tzanidis A, Lim S, Hannan RD, See F, Ugoni AM, Krum H. Combined  
557 angiotensin and endothelin receptor blockade attenuates adverse cardiac  
558 remodeling post-myocardial infarction in the rat: possible role of transforming  
559 growth factor beta(1). *J Mol Cell Cardiol.* 2001;33(5):969-981.
- 560 **42.** Uhal BD, Kim JK, Li X, Molina-Molina M. Angiotensin-TGF-beta 1 crosstalk in  
561 human idiopathic pulmonary fibrosis: autocrine mechanisms in myofibroblasts  
562 and macrophages. *Curr Pharm Des.* 2007;13(12):1247-1256.
- 563 **43.** Wynn TA. Common and unique mechanisms regulate fibrosis in various  
564 fibroproliferative diseases. *J Clin Invest.* 2007;117(3):524-529.
- 565 **44.** Wynn TA. Cellular and molecular mechanisms of fibrosis. *J Pathol.*  
566 2008;214(2):199-210.
- 567 **45.** Yamazaki M, Minota S, Sakurai H, et al. Expression of transforming growth  
568 factor-beta 1 and its relation to endomysial fibrosis in progressive muscular  
569 dystrophy. *Am J Pathol.* 1994;144(2):221-226.
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## Figure legends

**Figure 1.** TGF- $\beta$ 1 expression in fibroblast at 24 hours after incubation with angiotensin II ( $10^{-8}$  mol/L,  $10^{-7}$  mol/L, and  $10^{-7}$  mol/L) and/or losartan. □; 0 mol/L; ■,  $10^{-8}$  mol/L; ■,  $10^{-6}$  mol/L of losartan, respectively. Angiotensin II induced TGF- $\beta$ 1 expression in dose dependent manner (\* $p < .05$ ). Losartan blocked TGF- $\beta$ 1 expression. \* $p < .05$

**Figure 2.** Immunocytochemical staining of C2C12 cells for fast myosin heavy chain at 5days after incubation with different concentration of angiotensin II or losartan (A, control; B,  $10^{-8}$  mol/L of angiotensin II; C,  $10^{-8}$  mol/L of losartan). Myotubes are shown in red and nuclei are in blue (original magnification,  $\times 200$ ). D and E, comparison of fusion index of C2C12 differentiation with varied concentrations of angiotensin II or losartan, respectively. \* $p < .05$ .

**Figure 3.** Histologic evaluation of regenerating myofibers at 4weeks after contusion injury by hematoxylin and eosin staining of tibialis anterior muscle treated with different concentration of losartan (A, 0 mg/kg/day; B, 3 mg/kg/day; C, 10 mg/kg/day; D, 30 mg/kg/day; and E, 300 mg/kg/day) initiated immediately after injury. Regenerating myofibers were defined by centronucleated myofibers (original magnification,  $\times 200$ ). The graph (E) depicts quantification in number of regenerating myofibers in losartan treated animals compared with control animals. hpf, high-power field. \* $p < .05$  to control.

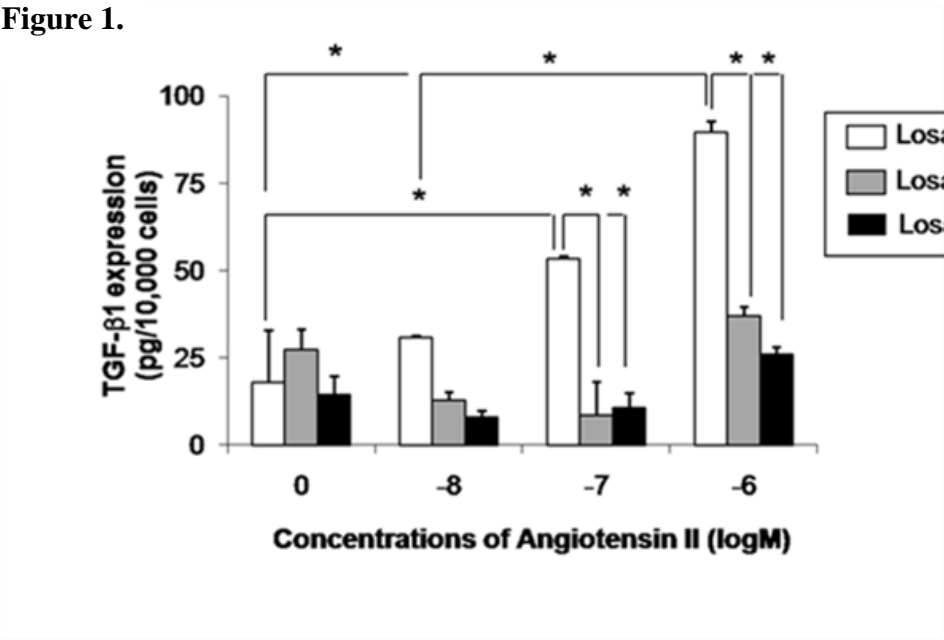
**Figure 4.** Histologic evaluation of the formation of scar tissue at 4weeks after contusion injury by Masson's trichrome staining (collagen: blue, myofibers: red, nuclei: black) of tibialis anterior muscle treated with different concentration of losartan (A, 0 mg/kg/day; B, 3 mg/kg/day; C, 10 mg/kg/day; D, 30 mg/kg/day; and E, 300 mg/kg/day) initiated immediately after injury. The ratio of the fibrotic area to the total cross-sectional area of 10 randomly selected slices was calculated to estimate the fibrosis formation (original magnification,  $\times 100$ ). The graph (E) depicts quantification of fibrotic area in losartan treated animals compared with control animals. hpf, high-power field. \* $p < .05$  to control.

**Figure 5.** A) Baseline MRI (subject 1) shows a partial tear at the left proximal myotendinous junction (white arrow) of the long head of the biceps femoris; also present is the surrounding edema with high-intensity signal in the hamstring muscle belly. B) Baseline MRI (subject 2) Grade 2 strain with partial thickness tear of the left biceps femoris at the mid aspect (white arrow), extends approximately 6 cm in the craniocaudal dimension.



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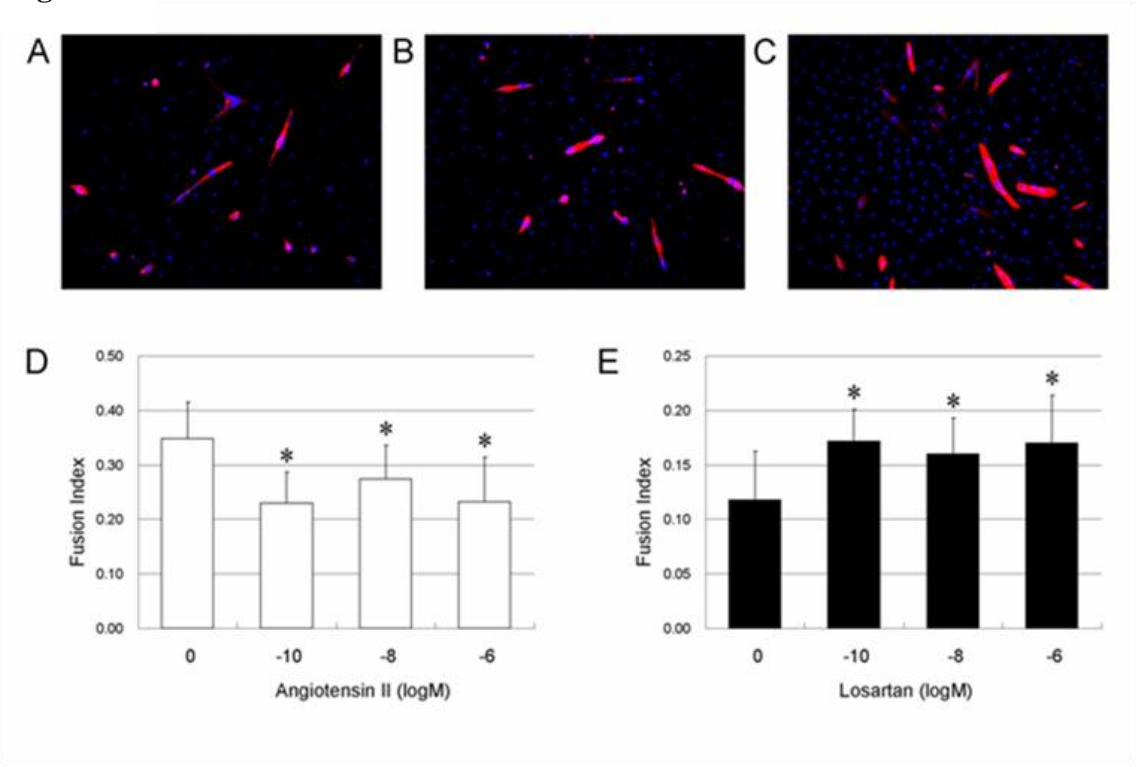
Figure 1.



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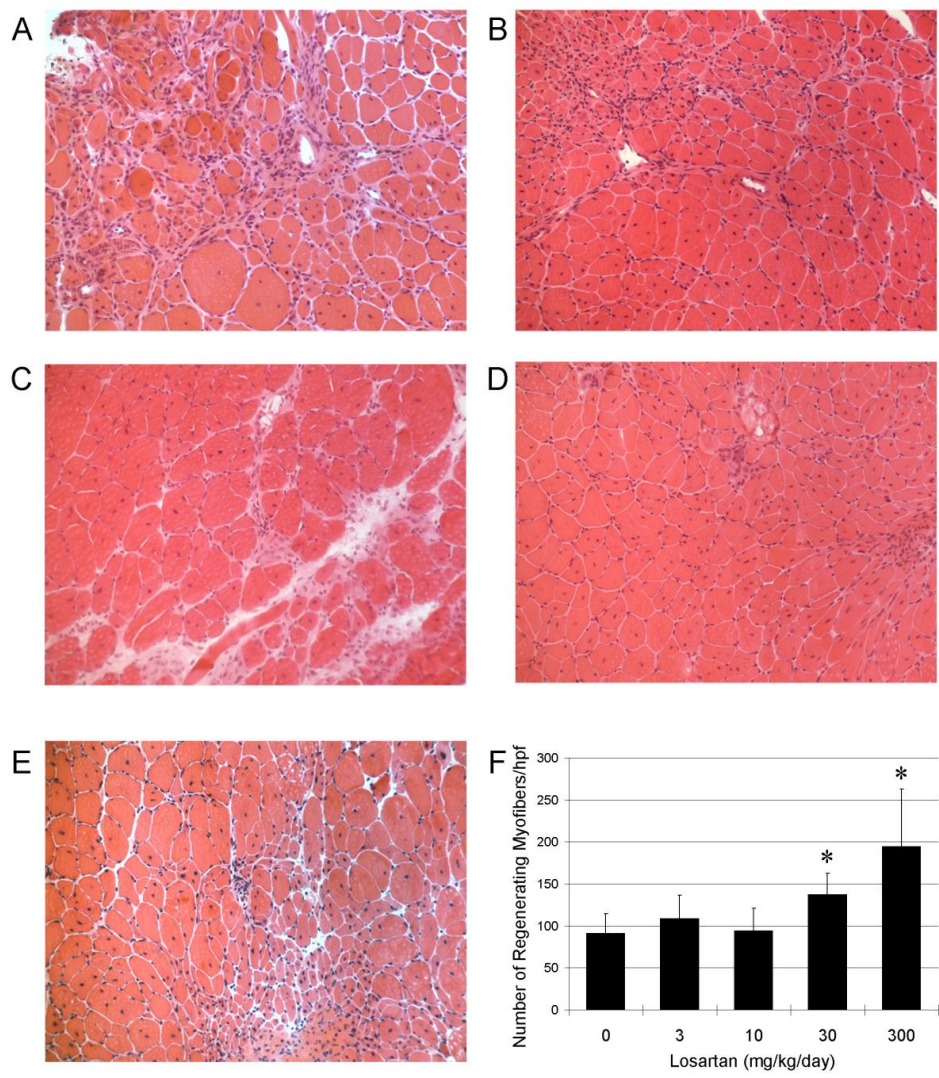
**Figure 2.**

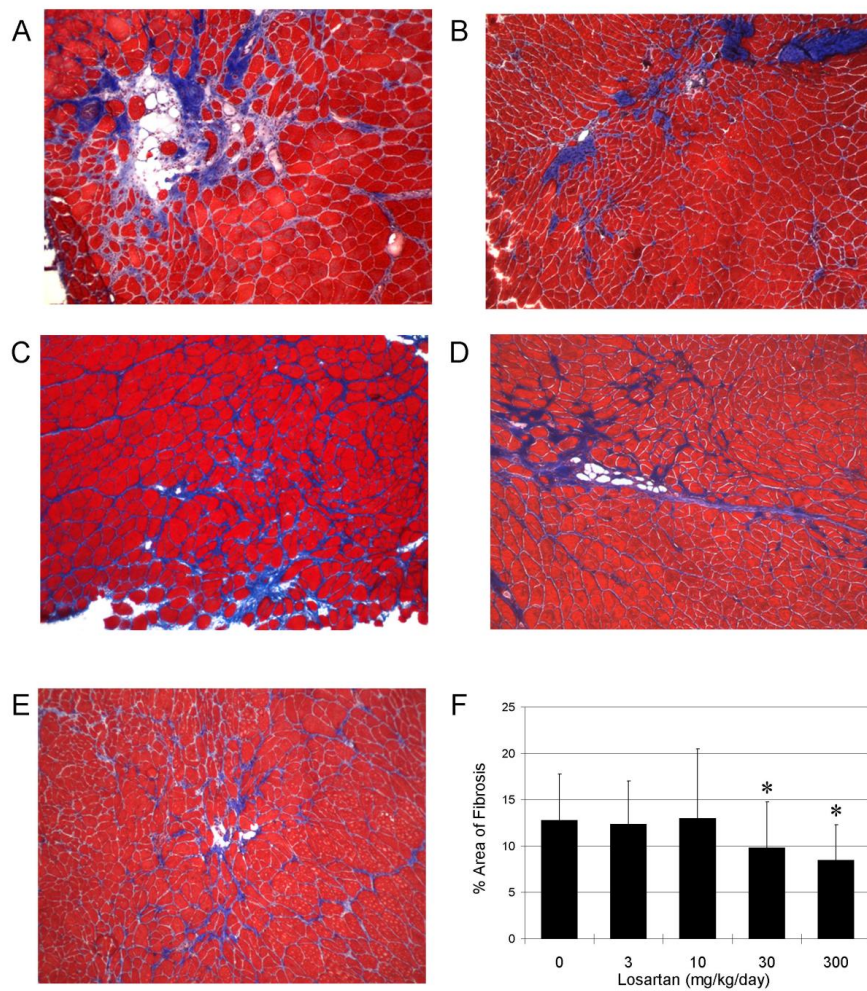


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**Figure 3.**



**Figure 4.**

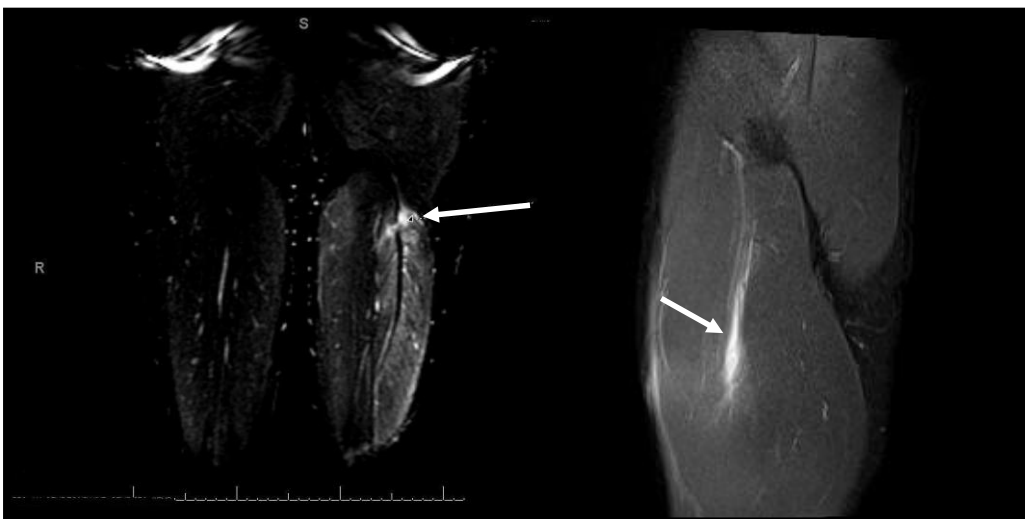
**Figure 5**

TABLE 1

## Results of Specific Peak Twitch and Tetanic Force

Group	Specific Twitch (N/cm2)	Peak Force	Specific Tetanic (N/cm2)	Peak Force
normal (noninjured)	19.24 ± 0.73		58.56 ± 11.51	
control (injured/untreated)	12.75 ± 2.51 <sup>b</sup>		44.78 ± 4.00 <sup>b</sup>	
3 mg/kg/day losartan	13.89 ± 2.15		49.46 ± 5.32	
10 mg/kg/day losartan	14.45 ± 1.42		56.25 ± 10.19	
30 mg/kg/day losartan	21.05 ± 5.26 <sup>a</sup>		74.16 ± 13.86 <sup>a</sup>	
300 mg/kg/day losartan	15.80 ± 3.77 <sup>a</sup>		67.77 ± 20.99 <sup>a</sup>	

<sup>a</sup>p < 0 .05 compared with control group<sup>b</sup>p < 0 .05 compared with normal group



TABLE 2

## Results of Strength and Flexibility Measurements

	1 <sup>st</sup> evaluation		2 <sup>nd</sup> evaluation		3 <sup>rd</sup> evaluation		4 <sup>th</sup> evaluation		5 <sup>th</sup> evaluation	
	Strength (%)	Pop angle (°)	Strength	Pop angle	Strength	Pop angle	Strength	Pop angle	Strength	Pop angle
Subject 1	47.2 / 54.1	30 (5)	71.0 / 79.6	5 (5)	85.5 / 92.6	5 (5)	91.5 / 83.5	5 (5)	83.3 / 107.1	5 (5)
Subject 2	59.6 / 60.1	13 (10)	101.4 / 85.5	24 (15)	103.8 / 92.5	15 (12)	110.5 / 99.7	26 (18)	132.5 / 110.8	14 (12)

Strength is presented as a percentage of the normal limb. Two values are presented; the first refers to the measurement performed at 30° of knee flexion and the second at 90° of knee flexion. Popliteus angles from both lower extremities are shown as the deficit to full extension; the uninjured side is shown in parentheses. Values shown are an average of three measurements performed.





# The Effect of Timing of Administration of Losartan on Skeletal Muscle Healing After Traumatic Injury

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## Introduction

Muscle injuries are a very common musculoskeletal problem encountered in military and sports medicine. In our laboratory, we have investigated several biological agents that provide benefit for accelerating the natural healing course of muscle injury. Specifically, we have focused our recent efforts on agents that inhibit muscle fibrosis via the inhibition of transforming growth factor- $\beta$ 1 (TGF- $\beta$ 1), a key cytokine in the fibrotic signaling pathway in skeletal muscle (1). Our previous study using a murine model of skeletal muscle injury revealed that losartan(LOS) treatment was effective at promoting muscle healing through an antifibrotic effect (2); however, the effective dose, which was administered immediately after muscle injury, was higher than the recommended dose used to treat hypertension in humans (10 mg/kg/day). Myostatin (MSTN) is a highly conserved TGF- $\beta$  superfamily member that is expressed in skeletal muscle. Reduction in MSTN expression in mice leads to muscle hypertrophy and hyperplasia. On the other hand, follistatin (FSTN) inhibits several members of the TGF- $\beta$  superfamily, including MSTN. Indeed, over-expression of FSTN induces a dramatic increase in muscle mass when over-expressed in transgenic mice (3).

## Objective

In this study we investigated the effect of LOS at the dosage clinically used in humans (10 mg/kg/day) when administered at different time points after contusion injury.

## Methods

**Animal model:** A muscle contusion injury was created in the tibialis anterior (TA) muscle of C57BL/6J wild-type mice. The administration of 10 mg/kg/day of LOS (40mg/L) was initiated on days 0, 3, 7 or 14 after injury and continued for 1 or 4 weeks. Tap water not supplemented with LOS was administered to the animals in the untreated injury control group, and in the non-injury group (normal group) (6 mice in each group). The LOS dosing was calculated based on the average fluid intake of the mice. Four weeks after injury, we performed physiological testing and harvested the TA muscles for histology. The dose of LOS at 10 mg/kg/day is equivalent to the clinical dose used to treat humans with high blood pressure (50 mg/day) (4).

**Physiological testing:** Four weeks after injury, we performed physiological testing. Under general anesthesia, the peroneal nerve was exposed by a lateral incision at the knee which was then hooked to a small electrode. To stabilize the hind limb, the knee and foot was secured to the platform with cloth tape. The foot was tied securely to the lever arm of 1500A Small Intact Muscle Test System (Aurora Scientific Inc., ON, Canada). The system has Dynamic Muscle Control Software (Aurora Scientific Inc.) to monitor muscle force. All data were displayed and stored on a computer and analyzed with the Dynamic Muscle Analysis Software (Aurora Scientific Inc.).

**Histology:** TA muscles harvested 4 weeks after injury were cryosectioned and stained for hematoxylin and eosin (H&E) and Masson's trichrome stain. The number of centronucleated regenerating myofibers was counted to evaluate muscle regeneration. Northern Eclipse software (Empix Image, Inc.) was used to analyze the total cross-sectional area of muscle fibrosis.

**Evaluation of Myostatin and Follistatin:** TA muscles harvested 1 week after injury were prepared for western blot analysis to determine the levels of MSTN and FSTN expression.

**Statistical analysis:** Significant differences were established by ANOVA followed by Scheffe's post hoc test. Statistical significance was defined as  $p < 0.05$ .

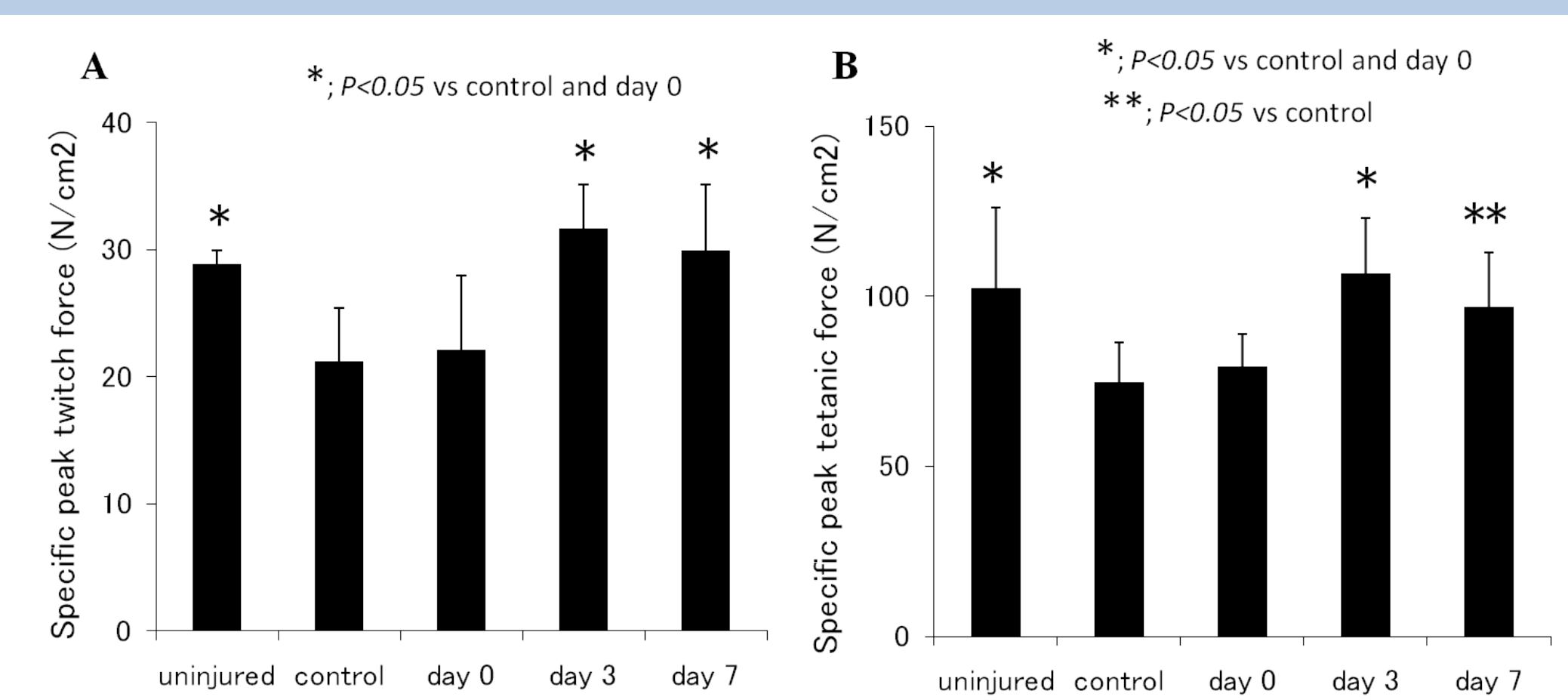


Figure1. Losartan Improved Muscle Strength Recovery after Contusion Injury

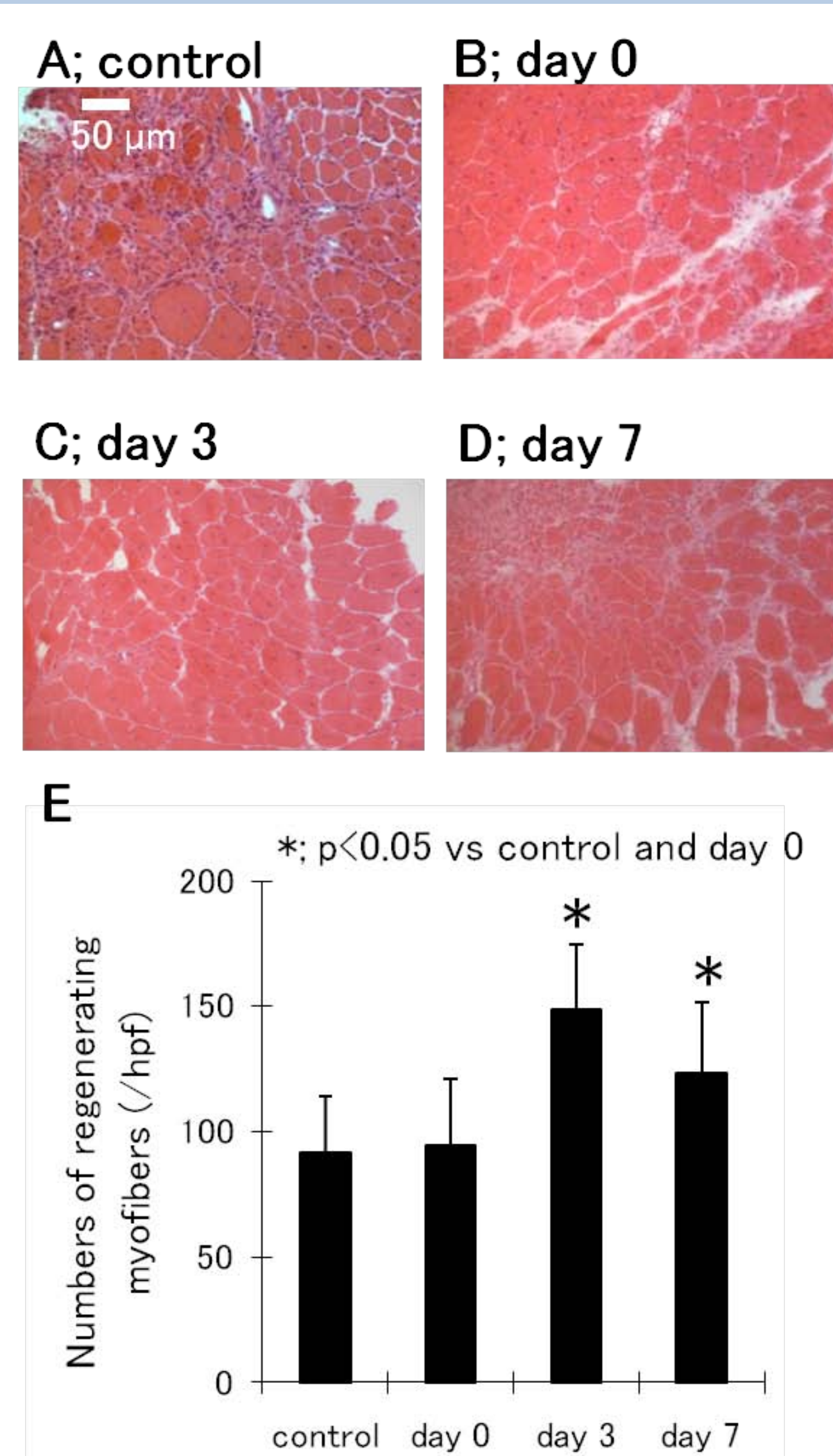


Figure 2. Histologic evaluation of regenerating myofibers

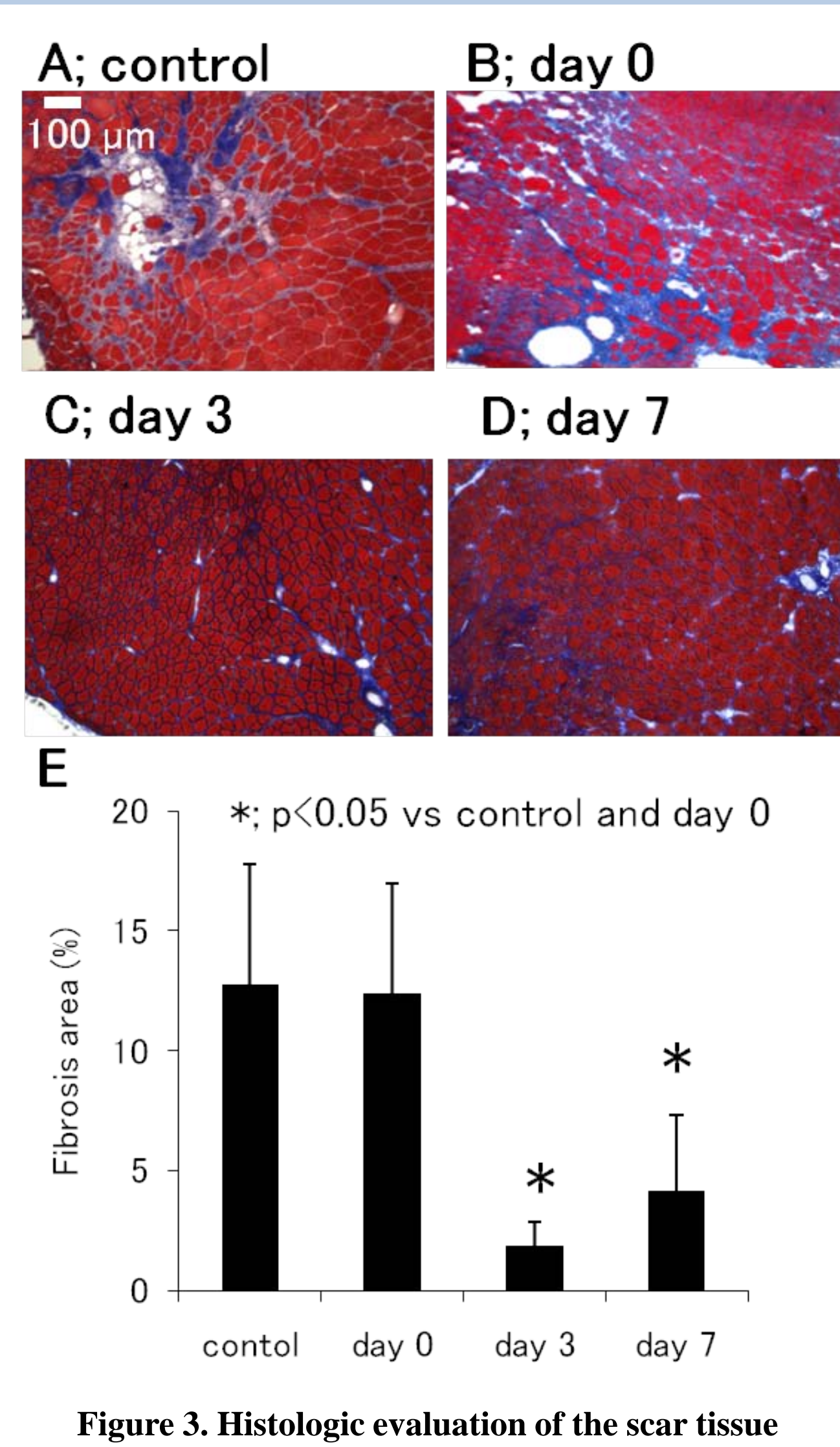


Figure 3. Histologic evaluation of the scar tissue

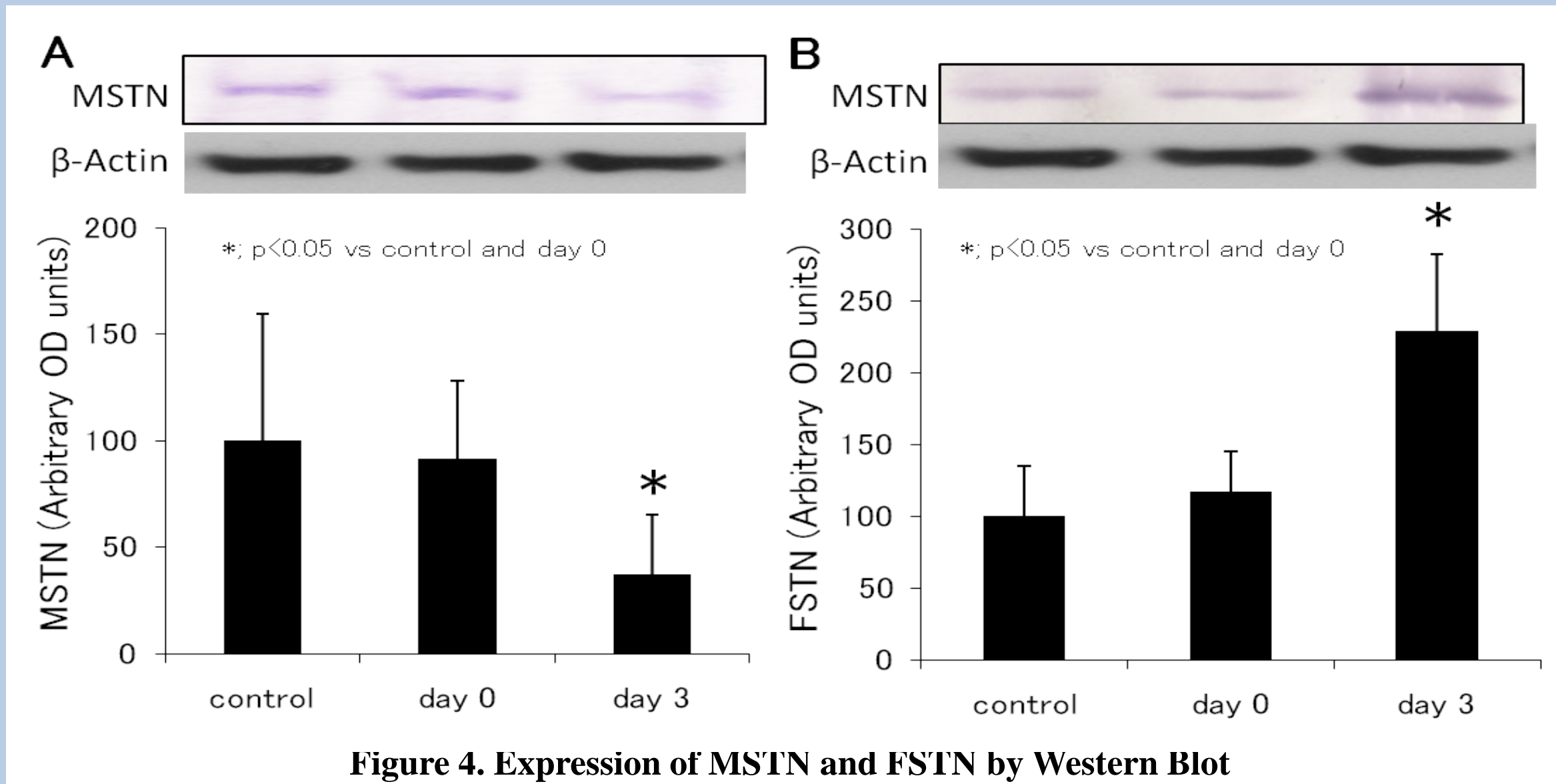


Figure 4. Expression of MSTN and FSTN by Western Blot

## Results

**Losartan Improved Muscle Strength Recovery after Contusion Injury:** Results from the physiological evaluations performed at 4 weeks post-injury (Figure 1A-B). Specific peak twitch and tetanic forces were significantly greater in mice where LOS treatment was initiated 3 days (31.70 3.42, 106.6 16.4N/cm<sup>2</sup>) after injury compared to the other groups (peak twitch 21.21 4.22, 22.13 5.83, and peak tetanic 74.81 11.7, 79.22 9.12N/cm<sup>2</sup>,  $p < 0.05$  respectively). The specific peak twitch and tetanic forces of the uninjured group (peak twitch; 28.85 1.09, peak tetanic; 102.3 23.8 N/cm<sup>2</sup>) was significantly greater than the control and day 0 groups. The specific peak twitch and tetanic forces of the day 7 group (peak twitch; 29.99 5.18, peak tetanic; 96.96 15.9N/cm<sup>2</sup>) was significantly greater than the control and day 0 groups ( $p < 0.05$  respectively, Figure 1A-B). No significant difference was observed between the day 3, day 7 and the normal groups.

**Effect of LOS on Muscle Regeneration after Contusion Injury:** The number of centronucleated regenerating myofibers, present in the contusion-injured muscle were counted and compared among the groups, 4 weeks after contusion injury (Figure 2A-E). We observed a significant increase in the number of centronucleated regenerating myofibers in the day 3 and day 7 groups (149.0 25.4, 123.3 28.3/hpf) compared with the other groups (control group; 91.32 23.0/hpf and day 0 group; 94.47 26.6/ hpf,  $p < 0.05$  respectively, Figure 2E).

**Effect of LOS on Muscle Fibrosis after Contusion Injury:** The areas of fibrotic scar tissue in the contusion injured muscle were calculated and compared among the groups, 4 weeks after contusion injury (Figure 3A-E). The day 3 and day 7 groups showed significantly less fibrosis (1.87 1.0% and 4.17 3.1%, respectively) than the control and day 0 groups (12.8 5.0%, 12.4 4.6%,  $p < 0.05$  respectively, Figure 3E).

**LOS effect on Follistatin and Myostatin expression:** The expression of MSTN in the day 3 group (-63% vs control) was significantly lower than in the control and day 0 (-9% vs control, 1 week after injury) groups 1 week after injury ( $p < 0.05$ , Figure 4A). Expression of FSTN in the day 3 group (+119% vs control) was significantly greater than in the control and day 0 groups (+17% vs control, 1 week after injury) 1 week after injury ( $p < 0.05$ , Figure 4B).

## Conclusion

Our previous results showed that we could obtain improvement of muscle healing when administering LOS immediately following injury; however, the dose of LOS used to obtain these results was 3 times the dose recommended for use in human patients suffering from hypertension. The current study demonstrated that the timing of LOS administration (3 days post-injury) is critical for obtaining optimal results using a lower and safer dose of LOS. In comparison with the other groups, we also observed an increase in the number of centronucleated myofibers, a decrease in the area of fibrosis, and an enhancement in muscle strength when LOS administration was initiated 3 days after muscle injury.

Administration of LOS 3 days after contusion injury, using a human dose equivalent for the treatment of hypertension (10 mg/kg/day), effectively leads to a reduction in MSTN expression, 1 week after injury. We also observed an increase in the number of centronucleated myofibers, a decrease in fibrosis, and an enhancement in muscle strength when LOS was administered 3 days after muscle injury. Wang et al. have demonstrated that LOS significantly blocked the increase of the MSTN protein by blocking angiotensin II, and indicated that angiotensin II increases MSTN expression through the AT1 receptor (5). These results may suggest that LOS administrated 3 days after injury can diminish angiotensin II-induced MSTN deposition of type I collagen which is mediated by the AT1 signaling pathway which would then allow for accelerated muscle regeneration.

In addition, the expression of FSTN was observed to be up-regulated in the day 3 group until 2 weeks after injury. It is well known that FSTN, a secreted protein, is able to bind and neutralize the actions of many members of the TGF- $\beta$  superfamily of proteins. In skeletal muscle, FSTN stimulates satellite cell proliferation and FSTN gene therapy has shown promise as a MSTN inhibitor to treat dystrophic mdx muscles (a mouse model of Duchenne muscular dystrophy) by increasing muscle size and strength and reducing fibrosis. Our results support these latter findings since the injured muscle treated with LOS shows an increase in FSTN expression and a decrease in MSTN expression, a finding that correlates with muscle regeneration and fibrosis formation. However, it remains unclear if LOS treatment acts directly on MSTN or through the up-regulation of FSTN.

This study demonstrated that LOS used at the dosage used to treat hypertension in humans is mediated directly through the inhibition of MSTN and/or the up-regulation of FSTN. This study strongly suggests that the use of LOS to expedite the muscle healing process could also be applied to other types of acute muscle injuries and may also be useful for the treatment of degenerative fibrotic muscle disorders.

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## References

- Li Y, *et al.*, Am J Pathol 161: 895-907, 2002.
- Bedair HS, *et al.*, Am J Sports Med 36: 1548-1554, 2008.
- Lee SJ, *et al.*, Proc Natl Acad Sci U S A 98: 9306-9311, 2001.
- Sasaki M, *et al.*, Life Sci 75: 869-880, 2004.
- Wang BW, *et al.*, J Endocrinol 197: 85-93, 2008.

Cellular Therapy for  
Compartment Syndrome

Consortium: University  
of Pittsburgh- Wake  
Forest University





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## Results

```
graph TD; Angiotensin_II[Angiotensin II] --> AT1[AT1]; AT1 --> Myostatin[Myostatin]; Myostatin --| Muscle_regeneration[Muscle regeneration]; Losartan((LOSARTAN)) --| Angiotensin_II; Extracellular_space[Extracellular space] --- AT1;
```

Figure 1. Signal pathway

We hypothesized that regulating the expression of AT1 during the inflammatory phase of the muscle healing process could accelerate muscle healing after skeletal muscle injury by promoting the beneficial aspects of the inflammation process. In this study, we investigated the expression of AT1, MSTN and MyoD (a regulator of muscle regeneration [4]) at different time points after contusion injury and at different initiation times of LOS administration (Day 0 group LOS started at the time of injury, Day 3 group LOS started 3 days after injury).

**Animal model:** The muscle contusion model was developed in the tibialis anterior (TA) muscle of C57BL/6J wild-type mice. LOS administration, at the concentration of 40mg per 1 liter of tap water, was initiated on either day 0 or 3 post-injury and continued until the end of the experiment. The control group was given drink tap water (6 mice per group). The dosing was calculated based on the average fluid intake of mice as 10 mg/kg/day respectively [1]. At 3, 7, and 14 days post-injury, we harvested the TA muscles of the mice for AT1 receptor, MSTN and MyoD expression analyses (Figure 2).

*Evaluation of the AT1 receptor, MSTN and MyoD Expression After LOS Therapy:*  
The TA muscles were harvested, cryosectioned and immunohistochemically stained 3 days and 1 week after injury using antibodies against the AT1 receptor and MSTN. TA muscles were also harvested at 1 and 2 weeks after injury and were cryosectioned and immunohistochemically stained using an antibody against MyoD. The expression of AT1, MSTN and MyoD positive areas were calculated using Northern Eclipse software (Empix Imaging Inc).

Statistical analysis: Differences between samples were assessed by ANOVA and Scheffe's F test as a post hoc test. Statistical significance was defined as  $p < 0.05$ .

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## References

1. Kobayashi, *et al.*, 56th ORS meeting, 2010.
2. Tharaux PL, *et al.*, *Hypertension*. 2000; 36: 330-336.
3. Bedair HS, *et al.*, *Am J Sports Med*. 2008; 36: 1548-1554.
4. Karalaki M, *et al.*, *In Vivo*. 2009; 23: 779-796.



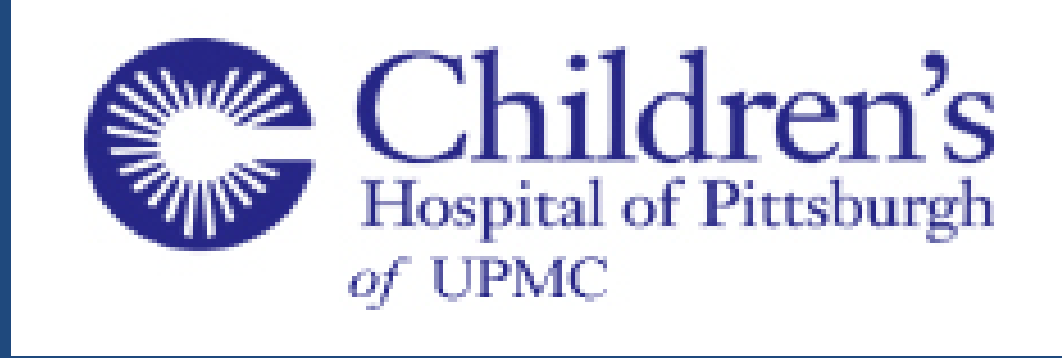


# Angiotensin II Receptor Blocker and Muscle Derived Stem Cell Transplantation for the Treatment for Contusion Skeletal Muscle Injuries in Mice

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## Introduction

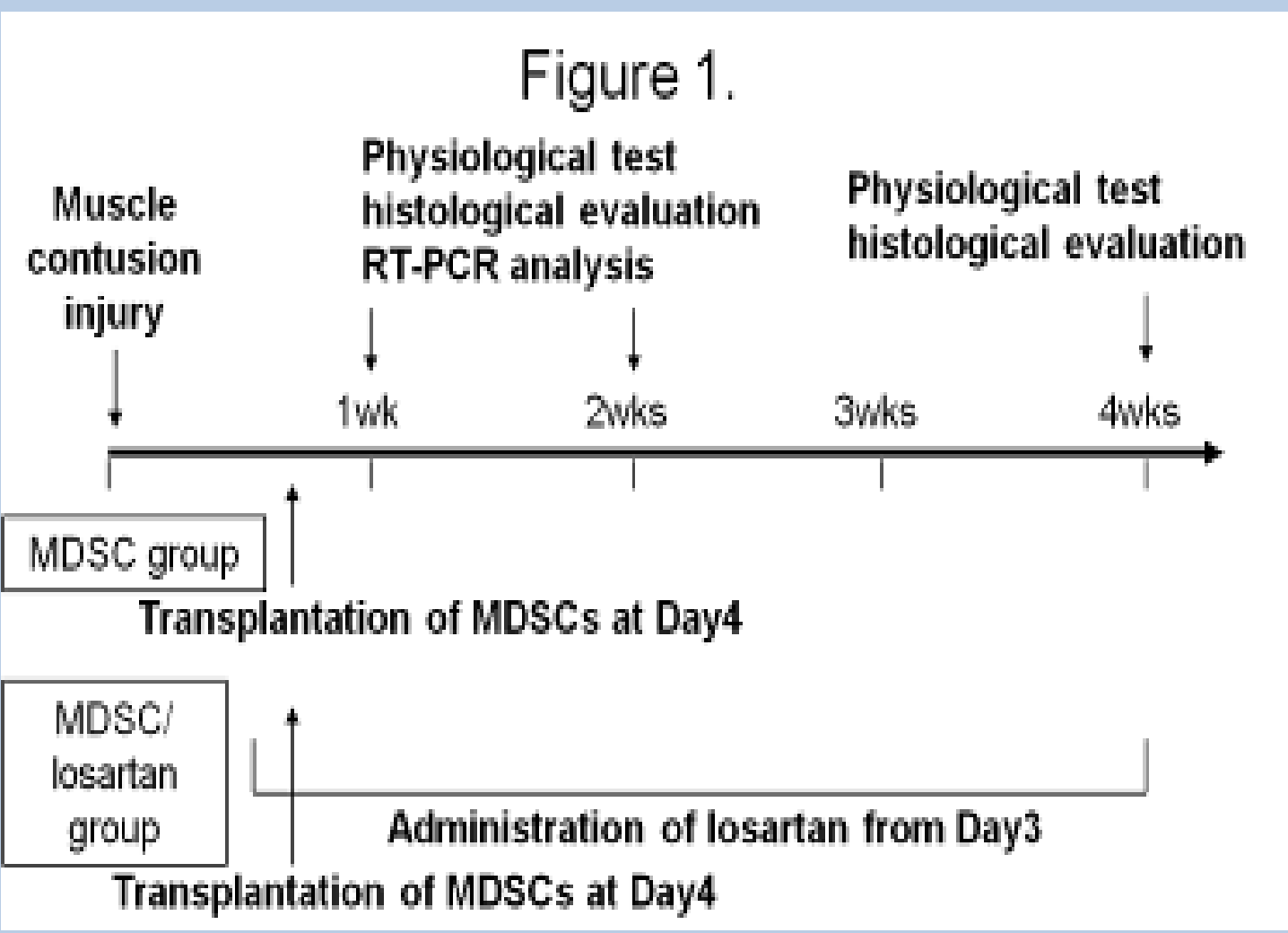
Muscle contusions are one of the most common muscle injuries in sports medicine. Although these injuries are capable of healing, incomplete functional recovery often occurs. We have previously reported that losartan, one of the FDA approved Angiotensin II Receptor Blockers (ARBs), can promote muscle healing by preventing fibrosis [1]. On the other hand, rapid revascularization after muscle injury is important for early muscle healing [2]. We have also previously shown that muscle derived stem cells (MDSCs) cells have a multilineage differentiation potential that includes myogenic and endothelial lineages [3]. At the last ORS meeting, we reported that the increase in functional recovery after MDSC transplantation in injured skeletal muscle was probably related to an increase in angiogenesis and a decrease in fibrosis formation; however, MDSCs transplantation alone could not completely inhibit fibrosis formation within the injured muscle.

## Objective

The aims of this study were 1) to analyze the effect of administrating losartan prior to MDSCs' transplantation had on muscle healing outcome after injury and 2) to investigate the mechanisms of action on the healing process when MDSCs' are transplanted along with losartan treatment.

## Methods

A contusion was performed on the tibialis anterior (TA) muscle of C57BL/6 wild-type (WT) mice [4]. MDSCs were isolated from 3-week-old WT mice using a preplate technique as previously described [5]. At 4 days post-injury, 3  $10^5$  MDSCs were transplanted directly into the injured TA muscle (n = 15 mice for each group). Concentrations of LOS (50mg) in 1 liter of drinking water were administered beginning 3 days post-injury until the end of the experiment. These doses were calculated based on the average fluid intake of mice as 10mg/kg/day. Mice were divided into 3 groups, 1) MDSC/losartan group, 2) MDSC group, and 3) injured control group with PBS injection and no losartan. At 1, 2, and 4 weeks post injury, a modified *in situ* force physiological testing was performed [6]. After the testing, animals were sacrificed and the TA muscles were harvested for histological evaluations. Statistical analysis was performed with ANOVA and Scheffe's F test as post hoc test. Statistical significance was defined as  $p < 0.05$ .



## Results

### MDSCs' Transplantation Enhanced Muscle Regeneration in Injured Muscle:

After hematoxin and eosin staining, the centronucleated regenerating myofibers in the injured muscle were counted and compared among the groups at 2 weeks post-injury. The MDSC treated groups (MDSC and MDSC/losartan groups) showed a significantly higher number of regenerating myofibers (MDSC group, 131.8  $\pm$  32.1; MDSC/losartan group, 132.4  $\pm$  28.5/hpf) when compared with the untreated control group (40.7  $\pm$  36.2/hpf) (Fig. 2A).

### Administration of Losartan Decreased Fibrosis Formation in Injured Muscle:

After Masson's trichrome staining, the area of fibrotic scar tissue was evaluated and compared among the groups at 4 weeks post-injury. The MDSC/losartan group showed significantly less fibrotic area (3.74  $\pm$  1.41%) when compared with either the control or MDSC groups (48.24  $\pm$  22.99 and 19.39  $\pm$  4.12%, respectively) (Fig. 2B).

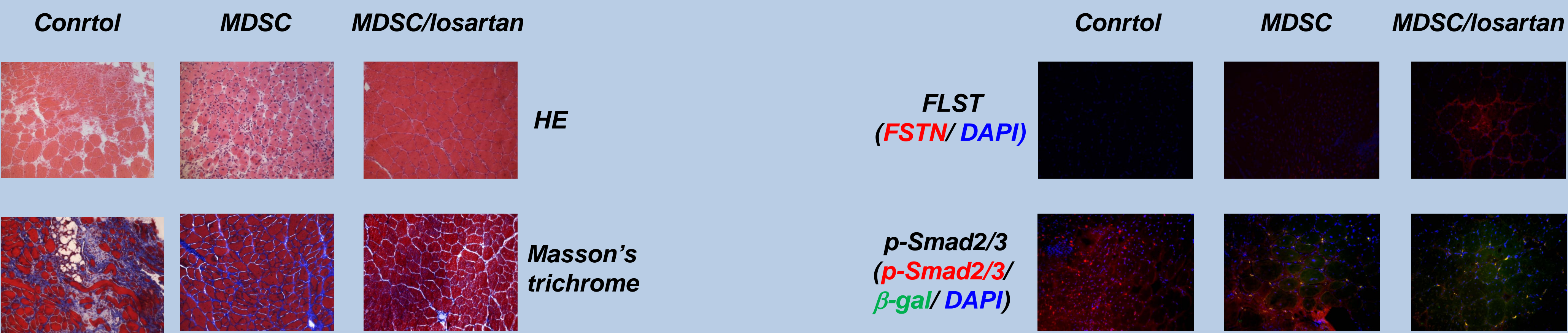
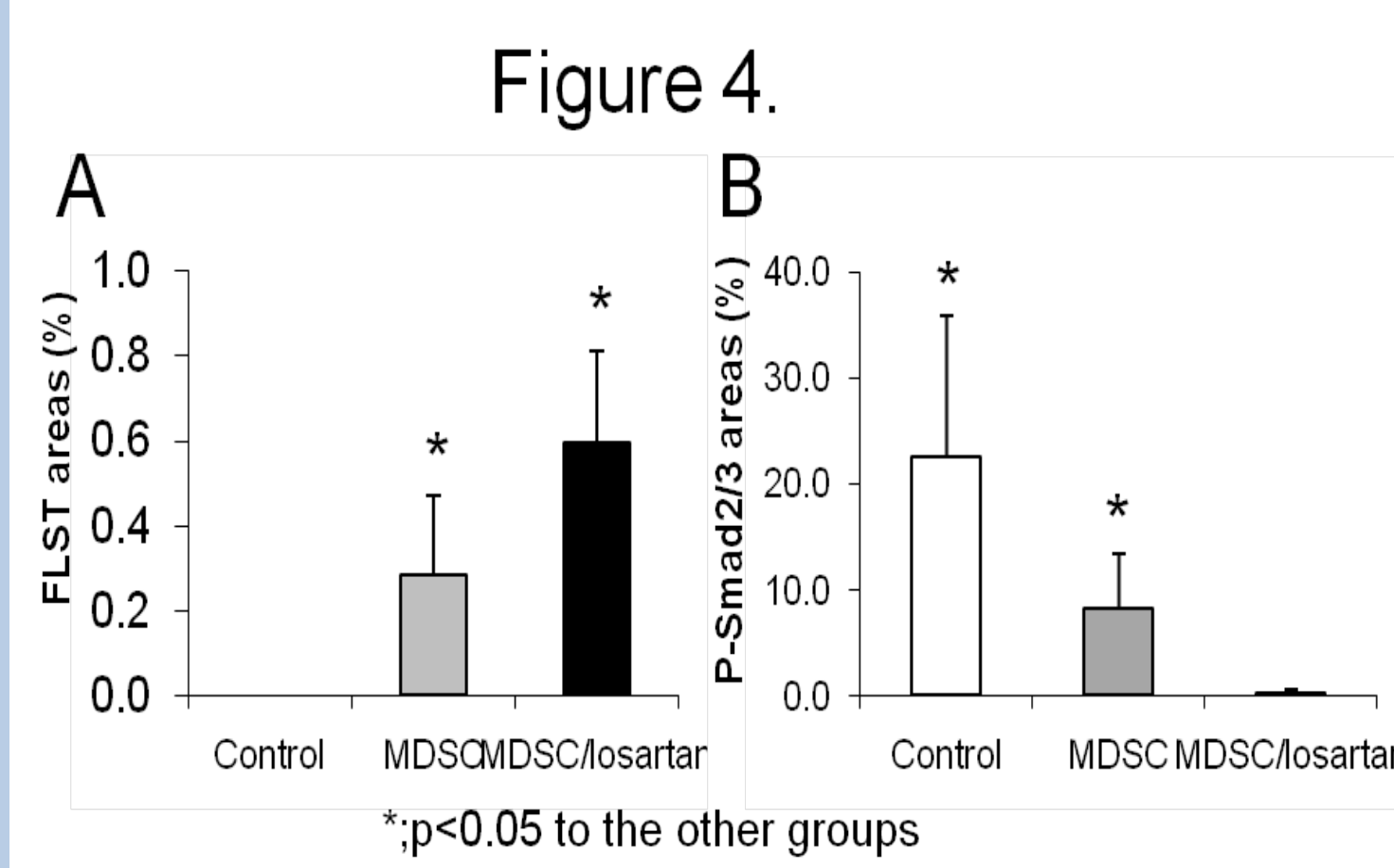
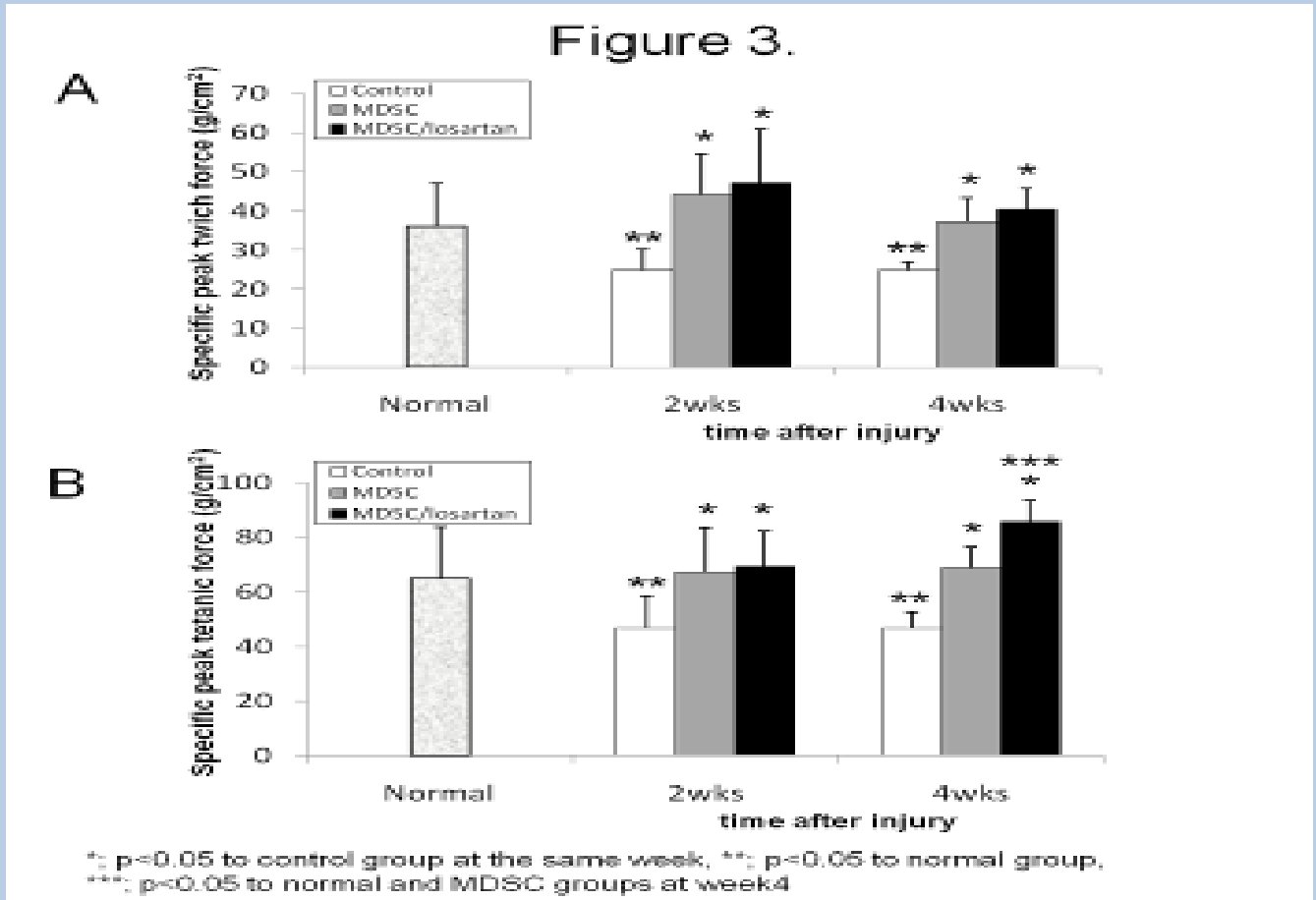
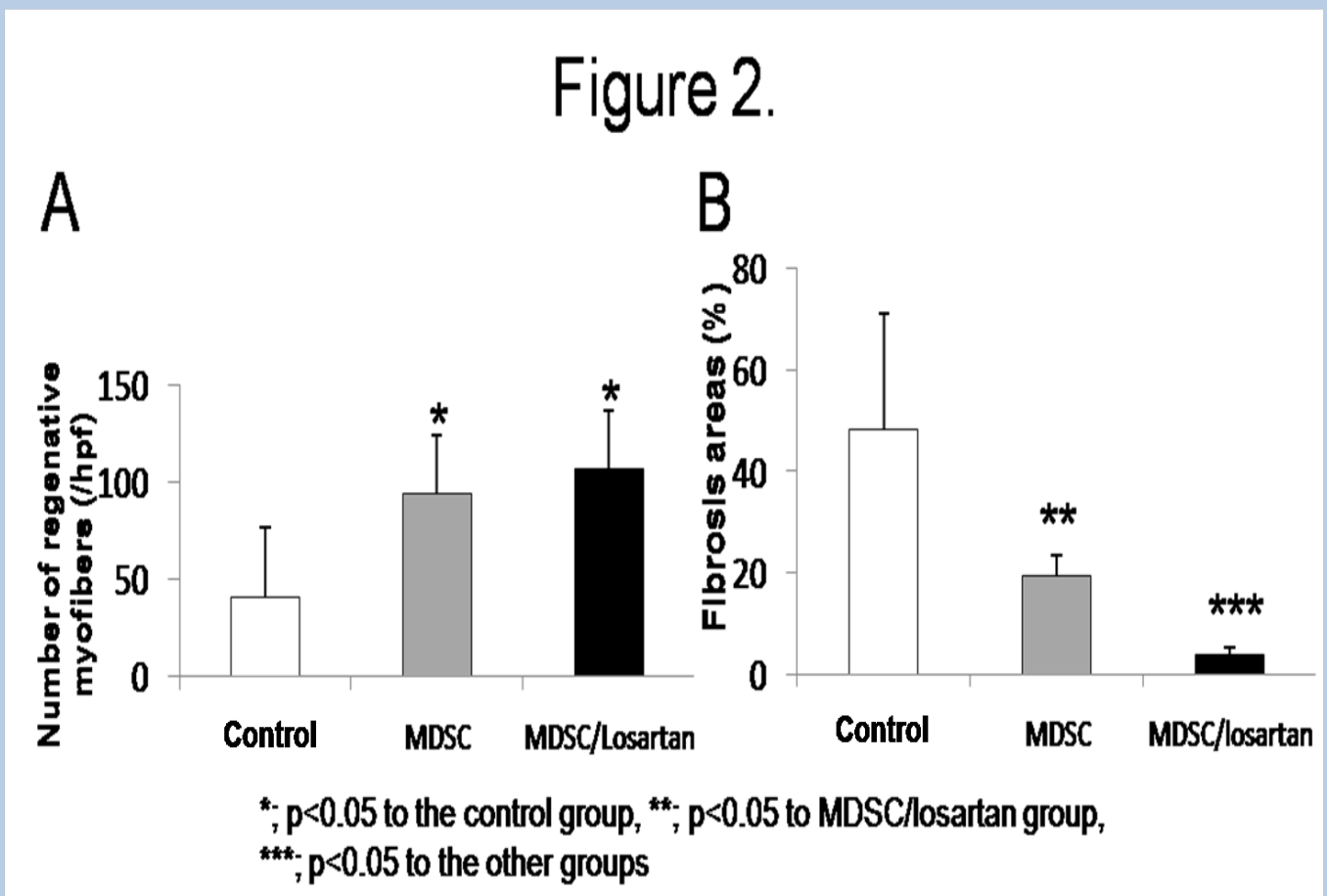
### MDSCs' Transplantation Showed Rapid Improvement of Muscle Strength:

At 2 weeks post-injury, the MDSC treated groups (MDSC and MDSC/losartan groups) showed significantly greater specific peak twitch and tetanic forces (twitch; 44.1  $\pm$  10.3 and 47.2  $\pm$  13.7, tetanic; 67.2  $\pm$  16.2 and 69.4  $\pm$  13.1g/cm<sup>2</sup>, respectively) when compared with control group (twitch; 24.9  $\pm$  5.3, tetanic; 46.8  $\pm$  11.6g/cm<sup>2</sup>). Moreover, there was no significant difference between the MDSC treated groups and normal group (twitch; 36.0  $\pm$  11.1, tetanic; 64.9  $\pm$  18.8g/cm<sup>2</sup>) (Fig. 3).

At 4 weeks after the injury, the control group showed significantly less specific twitch and tetanic forces (twitch; 13.8  $\pm$  2.0, tetanic; 17.4  $\pm$  2.2g/cm<sup>2</sup>) when compared with the other groups (MDSC and MDSC/losartan groups) (twitch; 20.6  $\pm$  3.1 and 22.4  $\pm$  2.1, tetanic; 25.6  $\pm$  2.7 and 31.9  $\pm$  2.9g/cm<sup>2</sup>, respectively). Interestingly, the MDSC/losartan group showed a significantly greater specific peak tetanic force when compared with the MDSC and normal groups (twitch; 20.0  $\pm$  0.8, tetanic; 24.1  $\pm$  0.8 g/cm<sup>2</sup>) (Fig. 3).

### MDSCs' transplanted after Losartan Treatment Enhanced FLST and Reduced p-Smad2/3 expression:

FLST expression areas in the injured TA muscles were measured and compared among the groups at 1 week post-injury. The MDSC/losartan group (0.60  $\pm$  0.22%) showed a significantly greater FLST expression when compared with the MDSC and control groups (0.29  $\pm$  0.19 and 0.00  $\pm$  0.00 %, respectively) (Fig. 4A). p-Smad 2/3 expression areas in the injured TA muscles were measured and compared among the groups at 2 weeks post-injury. The MDSC/losartan group showed significantly lower p-Smad 2/3 (0.25  $\pm$  0.34%) expression when compared with the control and MDSC groups (22.5  $\pm$  13.4 and 8.29  $\pm$  5.02%, respectively) (Fig. 4B).



## Conclusion

The combination therapy (losartan with MDSCs therapy) following contusion injury improved the overall skeletal muscle healing. We observed a larger number of centronucleated myofibers, less fibrosis, and better functional recovery in the combination therapy group when compared to PBS and MDSC only groups, 4 weeks after injury. Additionally, in this combination therapy, the expression of p-Smad 2/3, which is a transcription factor that regulates fibrosis deposition, was lower than in the other groups, 2 weeks after injury. These results suggest that the combination of losartan with MDSCs transplantation after skeletal muscle injury could represent an optimal biological treatments to accelerate muscle healing.

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### References

1. Bedair HS, et al., Am J Sport Med. 2008; 36: 1548-54.
2. Arsic N, et al., Mol Ther. 2004 Nov;10(5):844-54
3. Zeng B, et al., Nat Biotechnol. 2007; 25(9):1025-34.